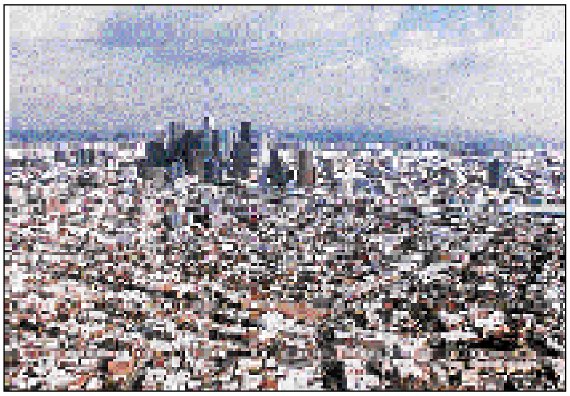
CHAPTER III

Achieving Seismic Safety in Buildings

California has many of the world's best earthquake safety experts and one of the most comprehensive building codes for earthquake resistance. Although these building codes and practices are generally adequate to protect lives, the Northridge earthquake demonstrated that they fall far short of what is needed to protect Californians from the economic disasters that major earthquakes cause. The unprecedented economic losses indicate that California still needs to make major improvements in building safety.

Los Angeles Times

A man peers into a collapsed parking structure.



A. Johnson

Figure 14. The Los Angeles region has over 8 million people in 3 million buildings, 240,000 of which were in regions of strong shaking during the Northridge earthquake.

The Northridge earthquake exposed a large urban building stock to intense shaking for the first time in California since the advent of modern building codes.

The Northridge earthquake exposed a large urban building stock to intense shaking for the first time in California since the advent of modern building codes. It lasted only about nine seconds, and much of its energy was directed at the rural Santa Susana Mountains; nevertheless, it vividly demonstrated that, although California has come a long way since the 1971 San Fernando earthquake, there are many improvements that still must be made to ensure that California's economy, as well as its citizens, can survive major urban earthquakes:

- *The quality of design and construction must be improved.* Poor quality in design, plan review, inspection, and construction were encountered over and over in the buildings damaged by the earthquake. California's current system of building design and construction encourages individual gambles that add up to significant risks, both for those who own the buildings and for those who depend on them as employees, tenants, or customers. Improving the quality of new buildings and making sure that remodeled buildings are seismically resistant will increase safety dramatically at a relatively minor increase in building costs.
- *Building codes must be improved.* Damage was expected and more prevalent in older buildings built to earlier codes. Modern buildings, in general, met the intended life safety level of the building code. Notable exceptions to this included poor performance in modern parking structures, tilt-up buildings, and welded-steel moment-frame buildings. Code changes have been proposed to begin to address these and other aspects for future construction. Future codes and seismic design guidelines should take better account of geologic and near-source effects on structures. In light of the extensive, albeit non-life-threatening, damage to modern buildings, the state should more actively support efforts to develop future codes, establish acceptable levels of earthquake risk in buildings, and develop design guidelines for meeting seismic performance objectives.
- *Nonstructural hazards must be reduced.* A building's heating and air conditioning systems, lighting fixtures, fire sprinklers, furniture, and equipment can become hazards in an earthquake if they are not adequately secured, and their loss can make a building unusable as surely as its collapse. Securing nonstructural elements is a relatively inexpensive way of improving seismic safety that can be applied to both new and existing buildings.
- *The risk from existing buildings must be reduced.* Improvements in codes and quality requirements for design and construction of new buildings will not reduce the risk posed by existing structures, and Northridge showed once again that older buildings are the most susceptible to damage in an earthquake. As a group, they pose California's single highest earthquake risk. The investment in these buildings is enormous; they cannot be replaced or retrofitted overnight, or for decades to come. However, local government programs can reduce this risk through zoning incentives and land use planning and by establishing triggers, such as significant remodeling projects, to require seismic upgrading.

General recommendations for achieving these goals are found at the end of the first sections of this chapter. Later parts of the chapter have specific recommendations for improving the seismic safety of several types of buildings that were damaged in the earthquake.

Improving Quality in Design and Construction

Damage resulting from a lack of quality showed up in all types of structures, from low-cost to very expensive single-family dwellings through multifamily apartment complexes to commercial buildings and highrise office buildings. Structures made of wood, steel, and concrete were all affected. A careful review of the damage has made it is clear that a significant portion of the damage was caused by one or more of the following:

- Inadequate engineering
- Inadequate design reviews
- Lack of understanding of the building code
- Misguided or incorrect construction practices
- Inadequate inspection or observation of construction

The greatest opportunity to ensure seismic safety is during a building's design and construction. The cost of ensuring quality is remarkably low—typically less than 2 percent of the cost of construction. The Northridge and other earthquakes have clearly and repeatedly demonstrated the remarkable effectiveness of paying attention to quality in reducing earthquake losses. Quality assurance is the single most important policy improvement needed to manage California's earthquake risk.

Though building code deficiencies may play a role in earthquake damage to some structures, a lack of quality at one or more points in the design and construction process is far more likely to be the primary culprit. As one experienced observer of the Northridge earthquake noted, in reference to damage of small wood-frame structures:

> Observation of the damages/losses suggests that good quality design, good plan check (review), good construction practices, good adherence to at least minimum or above codes, and good quality inspection by both private industry and local government would have reduced losses by a very high percentage. It appears that the low bidder caused more damage than the size or magnitude of the earthquake (Slosson, 1994).

Seismic safety in engineered structures is provided by three basic functions: design, construction, and oversight of these activities. The design responsibility typically falls to a professional—an architect or a civil or structural engineer. Construction is typically under the control of a general contractor. The oversight function that ensures seismic safety is carried out by government code enforcement agencies through plan checks and inspections and, in some cases, through the periodic observation of construction by design professionals.

California's current system of building design and construction encourages individual gambles that add up to significant risks.

In almost any human endeavor, one or more of three basic causes can be found to be responsible for a lack of quality:

- Limited money
- Limited knowledge
- Human error or carelessness

The vast majority of professional observers pointed to a lack of thoroughness, redundancy, and care as the primary cause of the unacceptable level of damage and financial loss. Many of these quality problems in the Northridge earthquake appear to have been financially driven. Continued economic pressures to lower design and construction costs have eroded the quality of both design and construction. Low-cost projects, which include both low-cost designs and minimum-quality materials, were present in significant failures in the Northridge earthquake.

Many owners who have only short-term interests in their buildings often opt for low-quality construction. However, each local government, and to an even greater extent state government, is adversely affected by the long-term, cumulative impact of these decisions, especially when earthquakes occur. The economic threat to California posed by future major earthquakes has arguably grown to become the single greatest threat to the state's competitiveness in the world market.

The lack of quality in construction is of concern in both new buildings and retrofit projects. Regarding damage to some retrofitted unreinforced masonry (URM) buildings, the City of Los Angeles' Department of Building and Safety's URM Task Force reported that much of the damage appeared to be caused by errors in design or plan checking and lack of adequate quality control.

Design Deficiencies

Quality assurance is the single most important policy improvement needed to manage California's earthquake risk.

The Northridge earthquake exposed numerous indications of minimal or inadequate design practices that were commonly associated with damage. For example, the Los Angeles URM Task Force indicated a number of common design deficiencies in URM retrofits, including erroneous design assumptions, missing wall anchors, and inadequate anchorage in new shotcrete walls. Closer attention to critical design considerations would have reduced or prevented damage on several other types of retrofitted buildings as well.

Newer buildings that were severely damaged also showed significant design deficiencies and poor engineering judgment. For example, tall, narrow plywood walls had oversized connections that were intended to keep the walls from rocking, indicating a basic lack of understanding of seismic design principles. Wider walls with more compatible proportions and smaller connections in other nearby buildings had very little damage. Similar design deficiencies were observed at a state-owned university building (Figure 15), which had very thick base plates and large anchor bolts to attempt to compensate for the small number of braced steel frames used.

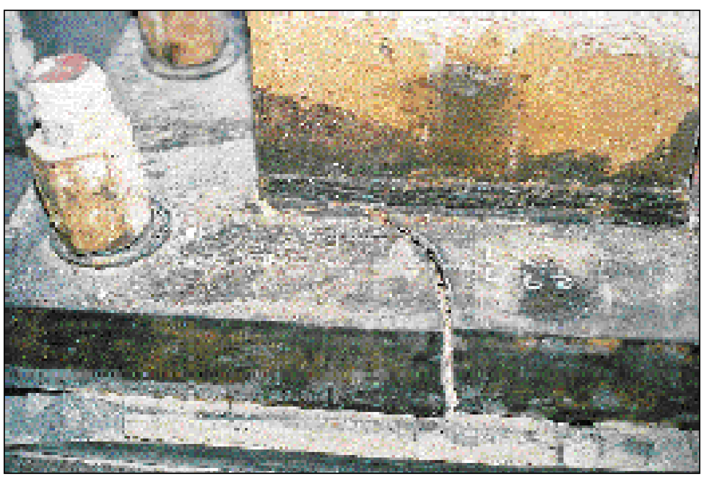

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Figure 15. A 4-inch-thick steel plate supporting the base of a column at the Oviatt Library at CSU Northridge. The plate fractured when the building was violently shaken.

Damage to tilt-up structures also indicated inadequacies in design. Inadequate reinforcing around anchors embedded in the tops of walls and pilasters is an example of poor design practice that contributed to damage. Faulty assumptions of lateral force distribution in calculations of out-of-plane support requirements may have also contributed to damage. Large gaps between wood roof members that were not considered in design but are present in hastily built, poor-quality construction were also identified as contributors to tilt-up failures.

An appropriate role for a designer is to provide an economical structure for the client. However, pursuit of low costs can evoke a classic conundrum of building design: inadequate, cheap designs drive out good but more expensive ones. The cheaper designs follow the letter of the code rather than its intent and often do not consider the structure's ultimate seismic performance. Engineers who design the least expensive structures are often rewarded with more work, producing even more pressure to minimize the structural elements. In these situations, the code, intended to be *minimum* requirements, instead becomes the *maximum* level to which buildings are designed. In highly repetitive construction, such as URM building retrofits, tilt-ups, and parking structures, the designs are refined many times, with the most inexpensive details reused—even if these details happen to be inferior (see Figure 16).

Overemphasis on low costs will also reduce the number of hours spent on important aspects of design such as developing alternate schemes and reviewing completed work. The drive for lower costs encourages repeated use of calculations and standard details, some of which may be inherently inadequate or not appropriate for all conditions. To reduce costs, engineers may simply leave drawings incomplete, change the design scope to include only a part of the structure (portions of some "designed" wood-frame buildings are built using only the rules of conventional construction) or leave parts of the structure to be "predesigned" or designed by contractors or suppliers (for example, wood and steel trusses, post-tensioned slabs, precast elements). The coordination of the final structure, particularly the lateral force path, can suffer in such cases, and the engineer of record may be difficult to identify (Adelman, 1994).

The pressure for more economical structures also encourages the use of design-build procedures, in which the contractor bids on both the design and the construction of the structure as a package. Since engineers and architects in design-build teams are working for the contractor, who must generally submit the low bid to get the job, they can be influenced to place a premium on economy and hasty construction techniques. The desire to survive in the highly competitive, often cutthroat, building industry can compromise the integrity and seismic safety of structures. Many professionals believe that design-builds can foster a conflict of interest for designers; at best, they create additional pressures to achieve the most economical design; at worst, they can produce poor construction and collapse-risk buildings.

Construction Deficiencies

The best design can be negated by poor construction, and earthquakes have a knack for exposing construction oversights. Poor quality and lack of attention to construction details played an important role in Northridge earthquake damage. There was some concern even before the Northridge earthquake that box nails were being used in the field where common nails were specified. Box nails (see Figure 17) are the same length as common nails, but their diameter is smaller, so they are less expensive and easier to drive but they are not as strong. So using box nails instead of common nails to construct a plywood diaphragm or wall reduces its strength substantially. Following investigations after the earthquake, the City of Los Angeles directed that the allowable capacity of nails in plywood diaphragms and walls must be reduced unless special inspection is provided to ensure that common nails are used and properly installed.

Another quality concern was the application of stucco. Many of the stucco walls that failed

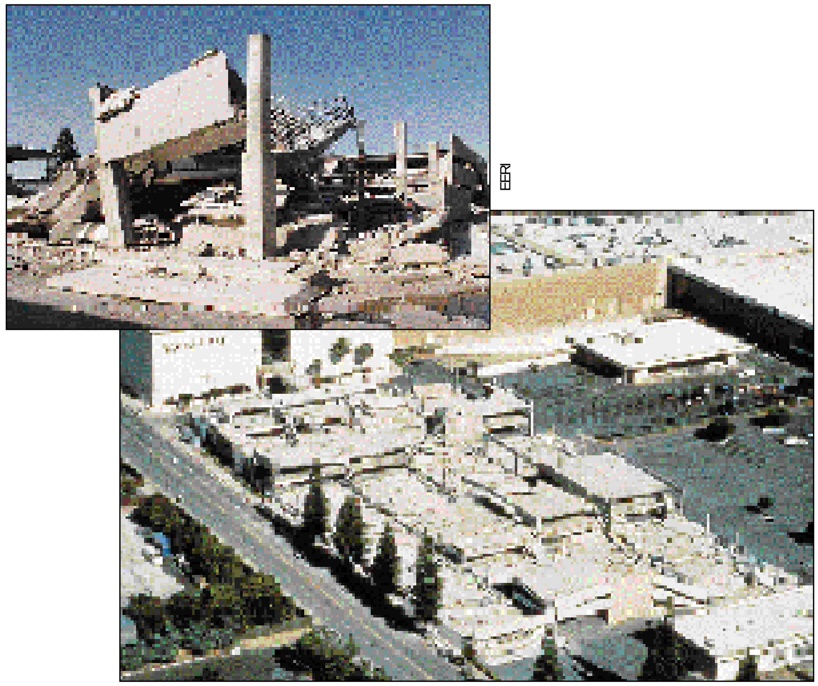

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Figure 16. This shopping mall parking structure collapsed primarily because its parts were not connected to each other. *Inset,* close-up of the same parking structure, showing separation of components.

were constructed by stapling wire mesh to wood-frame walls and applying the stucco over the mesh. The staples provided little earthquake resistance, and they held the mesh so tightly to the wall that the mesh did not become embedded in the stucco. Entire panels sheared off the wall when staples failed; even when they held, the initiation of cracking led to rapid disintegration of the stucco, which was unreinforced because the wire mesh was not adequately embedded.

Construction errors also contributed to damage in plywood walls. These errors included misplaced and bent anchor bolts; anchor bolts placed too close to the edge of concrete so they pulled out; bolt holes in sill plates drilled larger than necessary contributing to sill plates' splitting and sliding on the foundation; and wood framing members that were severely notched or had large holes cut through them to run pipes and wires without regard to structural integrity.

Poor quality and carelessness also caused damage in reinforced masonry and concrete structures. Errors included missing grout that made reinforcing steel ineffective and reinforcing steel that was placed too close to the exterior face of the concrete, causing the concrete to peel off.

Although the Uniform Building Code (UBC) contains requirements that prohibit this type of construction, code violations and dangerous construction will persist without better education, observation, and inspection.

Code Enforcement Deficiencies

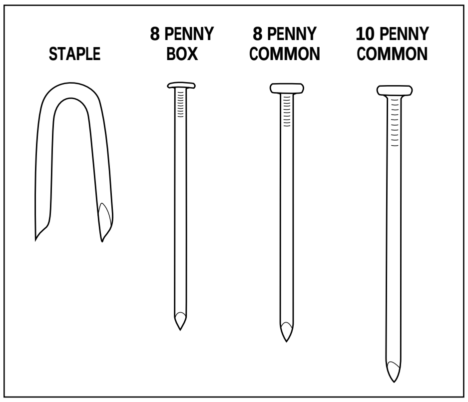

Figure 17. Smaller box nails and staples were routinely substituted for stronger common nails to reduce construction costs, also reducing earthquake resistance.

Inadequate quality of design or construction of buildings indicates that local governments' reviews of building plans or inspection of construction also was inadequate. Public school earthquake force requirements are the same as those for most apartment buildings, but public schools have fared far better in earthquakes. The primary reason for the superior structural performance of California's public schools compared to other, less regulated buildings is the detailed review of plans and calculations, particularly focused on the lateral force resisting system, and the formalized review and inspection of construction for schools. The structures that house the vast majority of our commercial infrastructure and people do not receive such attention. As a result, many of these buildings are not adequate to withstand shaking such as that experienced in the Northridge earthquake without extensive damage.

Improving Building Quality

Poor quality and lack of attention to construction details played an important role in Northridge earthquake damage.

The Commission believes the enhancement of quality in design and construction may be its most important single recommendation in response to Executive Order W-78-94. It is also one of the most problematic recommendations to define and measure in terms of effectiveness. However, unless quality is improved in the entire design-construction-inspection chain, efforts in other areas, such as code improvements, will be for naught. Policy makers, state and local government officials, owners, design professionals, and contractors must realize their shared responsibilities for seismic safety. Improving quality requires increasing accountability among owners, designers, and contractors.

Owners' Responsibilities

Building owners are typically not aware that they are primarily responsible for ensuring the quality of their construction. They are also responsible for the life safety aspects of their buildings both during and after construction. All too often, owners choose to be penny-wise and pound-foolish. Skimping on quality and seismic safety may save a few percent of the initial construction cost, but a damaging earthquake may devastate the real estate investment.

Owners must recognize that, though it is impossible to prevent all damage, they may be liable for failure to take reasonable measures to prevent injuries to employees, tenants, and customers. They should be made aware of their responsibilities so they can demand appropriate design and construction from the professionals who design and build their projects.

Quite often owners are faced with major earthquake losses because they didn't recognize the consequences of falling and damaged building contents. Contents should be installed to resist shaking and building distortion during earthquakes.

Recommendations

The Commission recommends that:

- Appropriate state agencies develop a strategy to make owners aware that:
  - They are responsible for seeing that reasonable and appropriate care is taken to hire qualified designers, inspectors, independent reviewers, and contractors and for clearly delineating the lines of responsibility for their functions in appropriate contract documents.
  - The building system with the lowest initial construction cost may actually have a shorter useful life and be significantly less resistant to earthquakes than

  a slightly more expensive system or a building of higher quality.
  - They are responsible for taking reasonable and appropriate precautions to protect building contents.
- Legislation be enacted to direct CalOSHA to adopt standards for bracing building contents and to promulgate and enforce regulations to require employers to include this information in their workplace safety and emergency plans.

Designers' Responsibilities

When a designer accepts a contract to design a building, the designer accepts a life safety trust from the people of the State of California. However, accountability for fulfilling that trust is practically nonexistent. State law must make it explicit that all designs that involve safety must have a clear line of responsibility for quality control from design through construction.

At present, there are a number of loopholes in this responsibility linkage. First, many designs include elements that are to be designed by the contractor. Although this practice may be cost effective and can yield satisfactory results, only the professional who designed the building is in a position to determine the adequacy of the completed building. The Commission believes that a single line of responsibility is the only method of ensuring the total seismic performance of a building.

A second significant loophole occurs during construction, when the best possible set of eyes—those of the designer—are not part of the construction review process. For reasons of liability and sometimes the owner's unwillingness to pay for such review, the designer of a project may not make site visits to view critical stages of construction and determine whether they comply with the construction documents. The Commission believes that construction oversight by the designer is an essential element of quality assurance and that it is not consistently present in construction statewide.

Designers must be accountable not only for the design of individual buildings but also for staying up to date regarding the state-of-the-art in earthquake-resistant design. Moreover, they must practice only within their areas of expertise. The state's currently accepted practice is providing life safety; the state has an obligation to ensure that those professing to hold this design expertise are truly qualified.

Architects are primarily responsible for the seismic safety of architectural elements in buildings as well as the coordination of architectural, structural, civil, mechanical, and electrical systems. Failures commonly occur during earthquakes because different building systems are not adequately coordinated. For example, fire sprinkler heads are sheared off by swinging ceiling systems; vents fall because they are not attached to ceilings; pipes leak when partitions are racked; large window panes break because their frames are not designed to accommodate building movements; and columns shear when partitions keep them from bending (see Figure 18).

The primary reason for the superior structural performance of California's public schools compared to other, less regulated buildings is the detailed review of plans and calculations.

Civil and structural engineers are primarily responsible for structural building elements in major projects. Mechanical engineers are responsible for the seismic safety of heating, ventilating, and air conditioning systems. Electrical engineers must design and ensure the adequacy of the electrical systems. Because of the ever-growing complexity of modern buildings, the coordination and delegation of design and construction duties is a critical part of achieving seismic safety. But all too often, owners do not insist on a clear delineation of responsibilities, and seismic safety suffers.

Current laws permit buildings and their parts to be designed by a variety of disciplines, including architects and civil, structural, mechanical, and electrical engineers. These professionals should be required by registration law to maintain a level of competence in seismic design commensurate with their responsibilities for such designs. Professional registration laws need to be strengthened to ensure that those who are responsible for seismic design have the appropriate qualifications.

The structural engineering profession was established specifically to provide specialized expertise

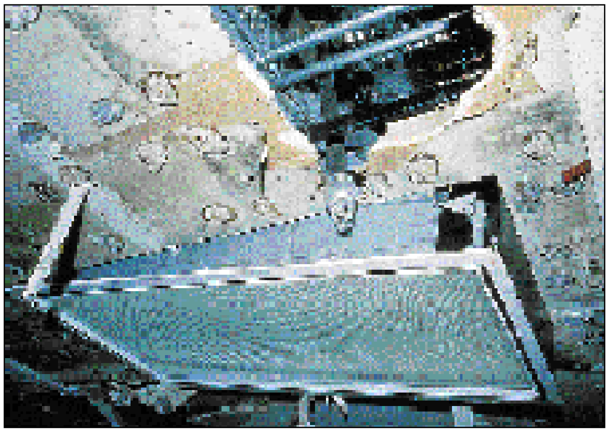
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Figure 18. When a ceiling panel (since removed) struck this sprinkler head during the earthquake, the pipe sprung a leak, causing extensive damage.

in seismic design. Currently there is no mandate in law or regulation that defines seismic design expertise, even though various agencies mandate the use of the structural engineering profession for certain types of critical structures. Moreover, there is no continuing education requirement that ensures maintenance of expertise in this area of rapidly evolving technology. The Commission believes that the expertise expected of the specialized field of structural engineering needs to be defined and that a program of continued education of that profession needs to be implemented and enforced.

Architects and civil, mechanical, and electrical engineers are not necessarily required to have formal education or work experience in the seismic safety of structures. In fact, it is still possible to graduate from most California colleges and universities in these professions with no formal coursework related to earthquakes. Many professionals receive their education and experience in other parts of the world and also have no formal education on earthquake safety. As a result, shoddy, marginal, and even incompetent designs are not uncommon. For these reasons, state regulations prohibit these professionals from practicing beyond their fields of demonstrated competence. However, few complaints regarding incompetence related to seismic design are filed with state licensing boards, and these regulations are rarely enforced.

Recommendations

The Commission recommends that:

- The California Building Standards Commission (CBSC) change the state's building standards to require that every building project have a single line of responsibility for the entire lateral force resisting system and vertical load carrying system assigned to the engineer or architect of record.
- CBSC amend the California Building Code to require designers of record to be responsible for a quality assurance program for structural and nonstructural elements for each project and, through personal knowledge, for the general compliance of construction with the contract documents.
- Legislation be enacted to hold designers harmless from claims, other than those claims specifically involved with observation of the work designed by the designer, when present at construction job sites.
- The Legislature periodically review licensing board activities to ensure that they are administering effective licensing examinations, requiring continuing education to maintain competency, and enforcing registration rules.
- The boards of registration for architects, engineers, and geologists hold hearings at the site of each damaging earthquake to determine the effectiveness of the boards in providing the necessary enforcement to ensure consumer protection and quality control over professional workmanship.
- The Board of Registration for Professional Engineers and Land Surveyors and the Board of Architectural Examiners raise the level of awareness of board rules that limit professional practice to areas of competency and the level of enforcement of those rules.
- Legislation be enacted to amend the title act for structural engineering to define the minimum level of seismic design expertise required of title holders.

Contractors' Responsibilities

The quality of the constructed product is greatly influenced by workmanship on the job site. The quality of construction can be improved when contractors and their workers understand the basic concept of earthquake-resistant construction: building elements that are well connected with quality materials and details perform well in earthquakes.

The state's construction industry is generally well intentioned and would like to produce quality buildings. Greater awareness in the construction industry of basic principles of earthquake-resistant construction will result in fewer details that are hastily installed and fewer parts of buildings being omitted entirely. The state needs to establish and encourage methods to transfer basic knowledge to the construction industry—contractors, job supervisors, and workers—so that earthquake safety and the importance of quality in ensuring safety reaches a high level of awareness.

Recommendations

The Commission recommends that:

- Legislation be enacted to require the Contractor's State Licensing Board to test candidates for a working knowledge of practical seismic safety principles in their contracting disciplines as part of the normal examination process and to require continuing education to ensure that contractors maintain competency in this area.
- The Contractor's State Licensing Board hold hearings at the site of each damaging earthquake to determine the effectiveness of the board's efforts to ensure consumer protection and quality control.

Building Code Enforcement Agencies' Responsibilities

The public expects building departments that enforce the building code to protect against deficiencies in design and construction. However, these departments vary dramatically in size and expertise throughout the state. Many lack budgets and personnel to thoroughly and consistently carry out the state's Riley Act, which requires checking building plans, issuing building permits, inspecting construction, and issuing certificates of occupancy for all new construction.

Plan checkers and building inspectors are responsible for making sure that building designs meet both the letter and the intent of building code provisions and that construction is carried out in accordance with the plans and good construction practice. As a matter of policy, plan checkers and inspectors should also notify the owner and the appropriate professional registration board if they believe that a designer or contractor is incompetent or is deliberately failing to follow appropriate procedures. Unfortunately, there are no guidelines or minimum standards for the performance and qualifications of plan checkers or inspectors; in fact, a significant number of state and local government building code enforcement agencies do not have any licensed building professionals on their staffs. This vital aspect of the overall construction process needs support if the quality of construction is to be improved.

Although private building plans are checked and construction inspected by local government plan checkers and inspectors who are independent of the building owner, the state and many local governments exempt their own building projects from such independent plan checking and inspection requirements. For example, the California State University (CSU) system, the University of California (UC) system, and the state Department of General Services do not have independent plan checking functions. Building failures such as the collapse of CSU Northridge's recently built parking structure in the Northridge earthquake and the collapse of the auditorium at CSU

Building elements that are well connected using quality materials and details perform well in earthquakes.

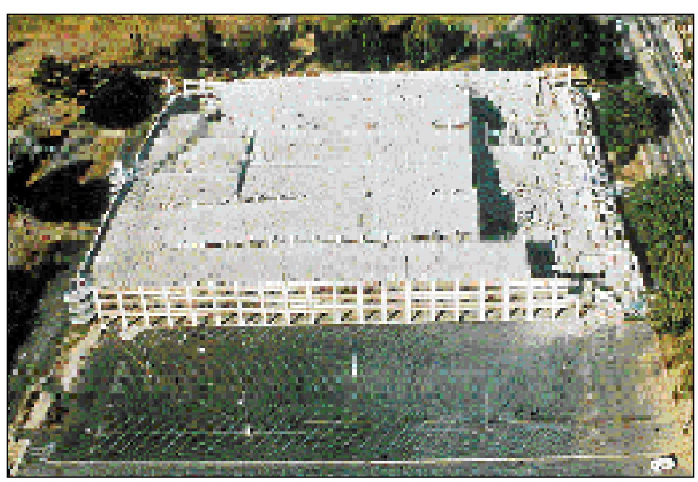

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Figure 19. Constructed in 1991, this CSU Northridge parking structure collapsed when interior columns failed.

Figure 20. Interior columns failed and girders fell off supports in this CSU Northridge parking structure.

The success of the Field Act in ensuring safe school buildings illustrates the importance of plan checking.

Long Beach without an earthquake are symptoms indicating that independent and competent plan checking of such structures is needed. Since there is an inherent conflict of interest when plan checkers are hired by the managers responsible for completing buildings, they should be responsible to another level of government: state university buildings might be inspected by the Division of State Architect or a qualified local building department. The success of the truly independent Field Act plan check process for construction of public schools illustrates the importance of this factor (see figures 19 and 20).

However, plan checking has practical limits. A designer can comply with the letter of the building code and still produce buildings that perform poorly because of the limitations of the code. This is particularly true for complex or irregular buildings that are often not included in the scope of the code. Building code enforcement agencies should be aware of these limitations of the code and require owners to engage peer reviewers starting at the early, conceptual stages of designs for important, irregular, or complex buildings. Peer review by independent design professionals with specific experience in unique building systems can ensure proper engineering judgment even though the code provides no direct guidance. Early intervention by peer reviewers is necessary to catch conceptual flaws that may be difficult, if not impossible, to address later. The typical cost of peer review, a small fraction of the cost of design, can pay off with enhanced, reliable seismic performance. As in medicine, a second opinion can save lives and reduce losses.

Recommendations

The Commission recommends that:

- Legislation be enacted to make structural plan checking of engineered buildings an act requiring professional licensing.
- CBSC amend the California Building Code to require all building code enforcement agencies to require owners of important, irregular, complex, or special-occupancy buildings to hire, as part of the permit process, independent peer reviewers whose involvement starts with schematic design phases and continues through construction.
- Legislation be enacted to require building inspectors and public and private plan checkers to be trained and certified by nationally recognized organizations and subject to continuing education requirements by recognized organizations in their areas of competence. Inspectors and plan checkers should be restricted from inspecting and checking plans beyond their areas of certification and competency.
- CBSC amplify what is already allowed by state law and amend the California Building Code to empower building departments to reject incomplete plans and collect additional fees for reconsideration of incomplete plans. Building code enforcement agencies should file complaints against designers and contractors who violate the building code or approved construction documents, and such complaints should receive priority over other complaints.
- CBSC—with the assistance of boards of professional registration, the Contractor's State Licensing Board, and inspection and plan check certification organizations—develop a standard method for filing complaints on repeat code violators and preparers of incomplete plans.

- Building code enforcement officials and professional associations work together to develop timely changes to the UBC and California amendments to the code to incorporate the changes recommended above.
- Legislation be enacted to require all state, local, and special agencies, including UC and CSU, to have a formal and independent building code enforcement entity with clear and appropriate enforcement, citation, and stop-work responsibilities and authority.

Improving Building Codes

At the heart of Governor Wilson's executive order is the question "Is the building code safe enough for earthquakes?" With few notable exceptions, the UBC provides an adequate level of life safety for new construction as long as the code is strictly applied during the design and construction of buildings and as long as the code is enforced with thorough plan reviews and inspection. As long as the current performance objectives are acceptable, the building code itself is not in need of a major overhaul, but far more attention to strict adherence to the code and the elimination of shoddy design and construction is clearly needed for earthquake-safe buildings. Recent changes to the earthquake requirements in the building code have not been adequately substantiated and do need to be more comprehensively verified in the future.

Since before the 1906 San Francisco earthquake, seismic design engineers have been developing building codes to achieve the goal of protecting lives by preventing structural collapse or massive wall failures. Revisions and refinement of California's seismic code provisions have traditionally been based on engineering research and observations of building damage—each significant earthquake has made its contribution to improving building safety.

The Northridge earthquake provided the first significant test of modern building codes. It indicated that, in general, buildings built to current codes achieve life safety performance if the codes are strictly applied during design and construction and enforced with thorough plan reviews and inspection. Most building owners did not anticipate the extent of damage that occurred in the Northridge earthquake. In the majority of cases the code's seismic performance objective of life safety was met. However, the Northridge earthquake caused structural and nonstructural damage to buildings far exceeding the expectations of owners and occupants of most of the damaged buildings. The financial losses from this earthquake were high for individual building owners, tenants, the real estate market in general, businesses such as insurance companies and lending institutions, local governments, and state and federal agencies. Improved performance can be accomplished by increased attention to quality in design and construction, better minimum standards and code rationale, and better code enforcement with only slight increases in cost.

As in medicine, a second opinion can save lives and reduce losses.

There were troubling exceptions to the performance of modern buildings in the Northridge earthquake: steel-frame and tilt-up buildings, above-grade concrete parking structures, and buildings located in areas that experienced violent ground motion did not perform to expectations.

Therefore, though modern construction generally fared well, some changes to the code development process are needed:

- Building materials, their connections, and code requirements must be more thoroughly substantiated with testing and independent evaluations.
- Major buildings situated near active faults or known geologic features should be designed to accommodate their unique effects on ground shaking.

Improving the codes themselves requires several steps:

- Improving accountability for codes.
- Establishing clear public policy on acceptable performance objectives.
- Supporting the monitoring, testing, research, and knowledge transfer needed to meet the desired objectives.

MODERN BUILDING CODES

For engineered structures, modern building codes—or at least their seismic, or lateral force, provisions—are generally considered to be the 1976 and later editions of the UBC. For conventional construction, which includes most single-family residences, codes that are considered equivalent to modern go as far back as 1949, depending on when the local jurisdiction adopted certain provisions such as requirements for foundation anchor bolts.

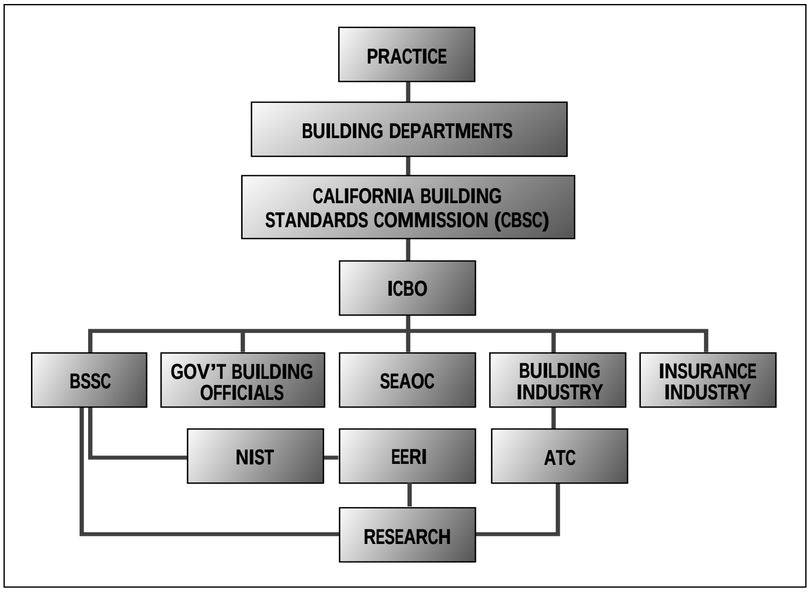


Figure 21. The building code development process for seismic safety is complex. It involves many organizations and steps, but no one is clearly responsible or accountable for its overall adequacy.

How Building Codes Are Developed and Administered

Californians rely on building codes as their foremost line of defense against the vulnerabilities of buildings. Codes cover all aspects of building design and construction, from seismic design requirements to heating, electrical, and plumbing specifications and down to details such as the proper type of nails. They regulate the work of owners, architects, designers, engineers, contractors, crafts workers, and others in the construction of habitable buildings.

Building codes were initially straightforward requirements for relatively simple buildings. The building code of 50 years ago was a single volume a few hundred pages long. Today, the codes used in California come in several volumes and are thousands of pages in length. Over the years, significant additions and changes have been made to address newly acquired knowledge and other considerations ranging from new types of materials and buildings to seismic concerns, as well as constantly changing laws and regulations governing design and construction of special buildings such as hospitals, schools, and essential services buildings. Many engineers believe this complexity leads to misunderstanding of design concepts and to the mistaken impression that following the code guarantees good performance.

California's building codes are based on the Uniform Building Code (UBC). Though the UBC is adopted, and sometimes modified, by local jurisdictions, state law sets minimum code standards that in only some cases are higher than the UBC's; for example, the state sets special provisions for hospitals, essential services facilities, and private and public schools.

The UBC is maintained and published by the International Conference of Building Officials (ICBO), but several other groups also contribute to its seismic safety development (Figure 21):

The International Conference of Building Officials is a private, nonprofit organization with state and local government building officials from the midwest and western United States as its voting members. ICBO publishes, maintains, and promotes the use of the UBC and its companion codes and standards. ICBO provides an evaluation service to ensure the seismic safety of a myriad of proprietary building products, connections, materials and other systems. ICBO also provides continuing education products, services, and administrative guidelines to its members.

Structural Engineers Association of California (SEAOC) has been involved in the development of seismic codes since the 1940s. Historically, ICBO has adopted the provisions of the SEAOC "Blue Book" for the UBC's seismic provisions. SEAOC's Seismology Committee spends thousands of volunteer hours per year on its main task of interpreting and updating of the "Blue Book," with travel costs and administrative and publishing support coming from SEAOC dues. Since its inception, the "Blue Book" has had two major revisions: the 1973 edition, which incorporated changes developed in response to the 1971 San Fernando earthquake and a 1988 rewrite that changed the basic format to better agree with ATC 3-06, which is described below.

Applied Technology Council (ATC) was established in 1971 to expand SEAOC's efforts in code development and technology transfer beyond what was possible with only volunteer efforts. ATC's first major project was ATC 3-06, *Tentative Provisions for the Development of Seismic Regu-*

lations for Buildings, which was intended to develop the basis for a completely new national seismic code. The document advanced the state-of-the-art considerably and developed a new format for seismic provisions, though buildings designed using these provisions were not much different from those designed using the practices adopted as a result of the 1971 San Fernando earthquake. Now nationally oriented, ATC organizes and implements research, code development, and technology transfer projects with funding from several sources including the National Science Foundation, the Federal Emergency Management Agency (FEMA), the U.S. Geological Survey, and the State of California.

Building Seismic Safety Council (BSSC) was established in 1979 as an independent, voluntary body under the auspices of the National Institute of Building Sciences (NIBS) as a direct result of federal interest in the seismic safety of buildings. Its primary role with respect to codes has been publishing updates to ATC 3-06, now called *National Earthquake Hazard Reduction Program Recommended Provisions for the Development of Seismic Regulations for New Buildings,* and assistance with its implementation. Revisions of the NEHRP provisions are done by committees as volunteers, as in the case of the "Blue Book," but on a national level. Travel and administration costs are funded by NIBS. Two competing seismic codes are now in use in this country—one based on SEAOC's recommendations and one based on BSSC's NEHRP recommendations.

California Building Standards Commission (CBSC) was established in 1979 to encourage uniformity in California's building codes and to minimize state-mandated changes to the UBC. The CBSC requires state agencies to justify all proposed amendments to the UBC before they can be adopted. Four state agencies can amend the UBC for seismic safety purposes: the CBSC, the Division of the State Architect (DSA), the Office of Statewide Health Planning and Development (OSHPD), and the Department of Housing and Community Development (HCD). State-approved amendments can be found in the California Building Code, which is published by the CBSC.

Improving Accountability in the Code Development Process

The administrative process for adopting changes to the building code works well in some respects; it is methodical, unbiased, and open to public scrutiny and participation. It can accommodate rapid code changes, as demonstrated by ICBO's recent emergency revisions to steel-frame building design requirements as a result of the Northridge earthquake, though it can take a decade or more for major changes to be incorporated into the code. However, it is a relatively obscure, technical, and bureaucratic process that is relegated to and dominated by interests with competing priorities and biases.

Though many organizations and individuals are active in the building code development and enforcement process, the state currently lacks a formal entity that can be held responsible for ensuring that appropriate reviews and policy changes are instituted, especially when questions arise regarding the adequacy of the building code after disasters. Accountability for building codes is now dispersed by a process that involves hundreds of volunteers and state and local building officials; as a result, key assumptions on which parts of the building codes rest are often accepted without adequate substantiation. This policy of benign neglect continues to place the state at a large and growing risk.

The economic threat to California posed by future major earthquakes has arguably grown to become the single greatest threat to the state's competitiveness in the world market.

National materials manufacturers and vendors, who have a legitimate financial interest in gaining and maintaining approval for their products in the codes, fund and oversee the development of information regarding their own products. The public interest is represented by private-sector volunteer design professionals and interested public officials whose participation is "volunteered" by their agencies but is often carried out largely on their own time, on top of their other duties. Too little of their time is available to make major advances in codes and their underlying philosophy. As a result, the code development process for seismic provisions is fragmented, often slow, lacking in accountability, and highly dependent on the availability of an informal network of volunteers. The coordination

Tobin

Figure 22. This industrial tilt-up building had its roof and wall partially collapse.

and integration of all these interests into a consistent, economical code procedure that provides an "acceptable" level of seismic performance has become extremely complex and may be beyond the capacity of the current processes.

Because seismic hazards are a national concern, participation in code matters involves seismic professionals and government officials from across the country, and the committees and meeting venues must reflect these geographic interests. Californians clearly have a far greater interest in the seismic provisions of the codes than other states, but that interest is only a part of the equation. Code change proposals and challenges to California proposals now come from many organizations and individuals other than California's structural engineers and building officials. So the code remains a compromise, and not all of what California needs is adopted.

The Northridge earthquake demonstrated a few notable shortcomings in the way in which technical changes to the building code are developed and verified. Recent changes in the code have not always been substantiated by comprehensive building materials testing and applied technology. As a result, billions of dollars of real estate investments now rely on unsubstantiated and, in some cases, potentially unreliable seismic safety requirements. Two examples illustrate this breakdown in the system of incorporating technical changes to the building code:

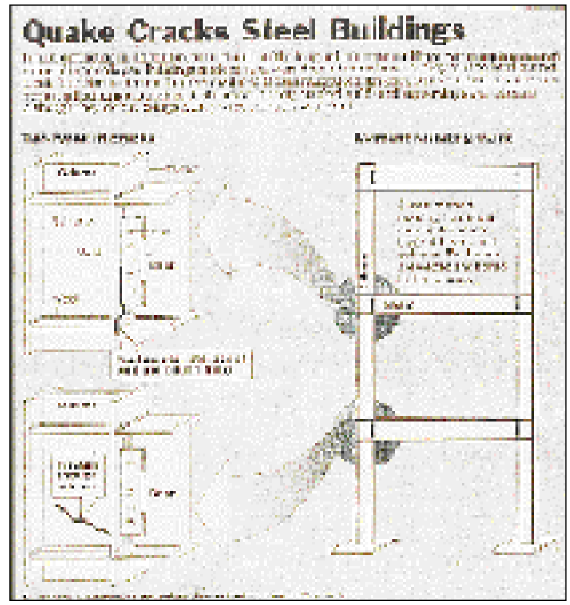
- The 1971 San Fernando earthquake showed that most tilt-up concrete buildings had an inherent weakness in the connections between the walls, roof, and floors. These connections failed, causing roofs to partially collapse and walls to fall away from buildings. Changes were made in the 1973 and 1976 editions of the building code that required wall-to-roof connections to be designed for higher forces and added new measures to avoid the premature splitting of wood members, but no substantiating tests to verify the new code requirements were ever carried out. The changes neglected to consider the flexibility of connections and the effects of their resulting displacements and overlooked the modes and sequences of response of the wall-to-roof connections as buildings move in response to ground motion. As a result, modern tilt-up buildings did not perform much better in the Northridge earthquake than pre-1973 tilt-ups. For an additional 20-plus years, tilt-up buildings have been built with less-than-reliable wall-to-roof connections (Figure 22).
- There were many failures of welded-steel moment-frame joints in the Northridge earthquake. The building codes allowed major investments in this type of construction although, in hindsight, there has clearly been a lack of substantiating research to verify the adequacy and reliability of welded-steel moment-frame joints. The code changes in the 1960s that allowed these fully welded steel frames were based on small-scale tests of steel beams that were on the order of ten times lighter and one-fourth the depth of beams now in wide use. Minor investments in full-scale tests back in the 1960s could have saved the industry from billions of dollars in Northridge earthquake losses alone. Had there been strictly enforced testing criteria for the acceptance and verification of building code changes, the problems with steel-frame joints could have been avoided (figures 23 and 24).

The code has become so complex that additional reliability and higher seismic performance cannot be achieved by simply increasing code requirements or making designs more conservative. This is best exemplified by current hospital design and construction requirements. Significant enhancements in hospital seismic performance were achieved primarily by improving quality control through rigorous plan checking and inspection. Though hospital seismic force requirements were arbitrarily increased by 50 percent, there is little evidence that this increase significantly enhanced seismic performance. The failures of nonstructural systems in hospitals indicate that their damage was due more to a lack of coordination in installing complex systems than to inadequate seismic force requirements in the code.

The complexity of the building code also makes it difficult for average building design professionals to keep up to date on the latest seismic provisions and the theories underlying them. It will do the state no good to improve the building code without commensurate improvements in the quality and competency of designers, contractors, and building code enforcers.

An additional problem is that in some cases, there is less profit in compliance with the intent of the code than there is in finding loopholes in it. In this game, those who charge small fees to design and build low-cost, low-quality buildings are the winners, rewarded with more work, so the minimum code requirements become the de facto maximum. The losers are those who may lose their lives, health, or economic well-being when a structure does not perform as expected. The Commission is not so naive as to believe that a new approach to seismic provisions in the code will entirely solve this societal problem, but present provisions make evasion of the code's intent too easy.

The fundamental approach for seismic design was set in the codes before development of our present-day knowledge regarding the nature of shaking and the response of structures to that motion. For the vast majority of buildings, it works quite well. Continuous improvements in the strength or capacity of buildings to withstand motions have been made as needed. The use of traditional elastic design techniques, in which the actual nonlinear response of the structure is not well represented, has also required continual adjustments to the code. During development of lateral force provisions in the 1980s, it was concluded that the expected shaking should be specified more precisely, and concepts such as peak ground acceleration, effective peak ground acceleration, and design response spectra were introduced into practice. However, this has not changed the code's original primary focus, which has been on design for adequate overall capacity in broad regional earthquake zones to maintain life safety. It would be difficult to accommodate unusual cases of structural dynamic irregularities, or the potential for unusual shaking, in the current code format without expensive penalties to all buildings.



Los Angeles Times

Figure 23. Though no steel-frame buildings collapsed, cracks in connections have stimulated efforts to substantiate building code requirements.

Recommendations

The Commission recommends that:

- Legislation be enacted to designate CBSC as the entity responsible for the adequacy of the seismic safety codes and standards for all buildings in California. CBSC should ensure that building codes and their administration meet the state's acceptable levels of seismic risk through various actions, including but not limited to:

EERI

Figure 24. Cracks in slightly damaged steel buildings were often undetected until months after the earthquake.

  - Ensuring the adequacy of existing and future seismic safety requirements in the model codes and state amendments.
  - Developing and adopting new seismic safety requirements for amendments to the building code for statewide applications.
- Legislation be enacted to authorize CBSC to establish a task force including other affected and interested agencies and organizations to develop plans to fulfill this responsibility within one year of the above legislation.

Higher seismic performance cannot be achieved by simply increasing code requirements.

Simplified code provisions for most simple buildings should require minimal interpretation skills and reflect the educational background and seismic awareness of average design professionals and code enforcers. The CBSC should also consider establishing comprehensive guidelines that go beyond the code and can be referenced in future codes for special occupancy buildings, essential services buildings, complex or irregular buildings, and buildings on unusual sites by the year 2000. These guidelines are needed for those few buildings in California's building stock that demand and deserve refinements above and beyond simple, prescriptive building code requirements. The guidelines should:

- Emphasize a variety of earthquake performance objectives so that owners and designers can explore options and select from a variety of approaches and systems to achieve desired levels of seismic risk.
- Define materials testing and building system verification and reliability requirements.
- Give parameters for design and analysis of building systems that reflect realistic earthquake ground motions, response, damage limit states, variability, and uncertainty of building systems.
- Outline procedures for independent reviews, quality assurance, interpretations, and enforcement procedures required for their appropriate application.

Building Code Performance Objectives

Observations from the Northridge earthquake have led the Commission to conclude that the time has come to add new tools to current procedures to design and build earthquake-resistant structures in California and to introduce responsibility and accountability into the process of code development. A new seismic design methodology is needed that more directly considers our current knowledge of ground motion and nonlinear structural behavior and that will better predict levels of performance and damage. The present codes do not provide for multiple performance objectives that would allow building owners, architects, engineers, and the financial community to make more informed—and therefore, perhaps, better—decisions regarding the performance of structures in the event of an earthquake.

Following the Northridge earthquake, public attention was on loss of life, high-profile structural failures, and enormous economic losses. Even though the vast majority of buildings did not collapse, there was a perception that overall building performance was unacceptable and that building codes and the construction process may not be adequate. The stated purpose of the Unified Building Code is potentially misleading to the public:

> The purpose of this code is to provide minimum standards to safeguard life or limb, health, property and public welfare by regulating and controlling the design, construction, quality of materials, use and occupancy, location and maintenance of all buildings and structures within this jurisdiction and certain equipment specifically regulated herein.

The general public is not aware that the intended performance objectives of today's building codes permit—even expect—substantial damage from strong shaking. Most believe that buildings constructed to modern codes, as well as retrofitted buildings, would not be significantly damaged in events such as the Northridge earthquake.

The intent of the current seismic provisions of the UBC, as described in the SEAOC "Blue Book" commentary, is that:

> Structures designed in conformance with these Recommendations should, in general, be able to:
>
> Resist a minor level of earthquake ground motion without damage;
>
> Resist a moderate level of earthquake ground motion without structural damage, but possibly experience some nonstructural damage;
>
> Resist a major level of earthquake ground motion having an intensity equal to the strongest either experienced or forecast for the building site, without collapse, but possibly with some structural as well as nonstructural damage (SEAOC, 1990).

The performance objectives implied (though not stated) in building codes have not materially changed over the years. Changes to the codes have been in the requirements felt necessary to meet those seismic goals. Modern codes have the same goals as the older codes, but buildings built to the older codes are generally more vulnerable because they were designed and constructed to less comprehensive seismic requirements. For example, reinforced concrete frame requirements in the code were enhanced dramatically in the 1976 edition of the UBC.

Did Buildings Meet the Code's Objectives?

A complicating factor in any discussion of how well building codes achieved their intended result in an earthquake is that any buildings being studied after a damaging earthquake like Northridge are the products of multiple building codes. The infinite variety of buildings have been designed, constructed, remodeled, renovated, and repaired over decades to different codes and are often a combination of different types and strengths of materials. Seismic considerations first appeared in California building codes in the early part of this century and the codes have been amended many times. Significant changes to seismic requirements occur in the codes following large damaging earthquakes (for example, the 1933 Long Beach and 1971 San Fernando earthquakes) in addition to regular code changes. It is also very difficult to know the intensity of shaking that individual buildings were subjected to in an earthquake. Although some structures are instrumented to gather such data, usually only educated estimates are available regarding the intensity of shaking that any given structure experienced.

Despite these complexities, the Northridge earthquake did provide a valuable test of seismic building codes. A large and varied inventory of structures was subjected to intense accelerations roughly comparable to seismic design assumptions of modern codes (post-1976). The amount of energy produced by the motion and transferred into the structures was large enough in many cases to push buildings beyond the point where damage began to occur. The energy in such a situation seeks out weaknesses and exposes poor quality or errors in design and construction.

To assess *current* seismic codes, the focus must be on the damage to modern, post-1976 buildings. A number of the structures that suffered spectacular collapses in the Northridge earthquake (for example, Bullocks, the Kaiser office building, and the Northridge Meadows apartment complex) were built to codes that predated the changes made following the 1971 San Fernando earthquake.

From the perspective of the code's primary objective of life safety, buildings built to post-1976 codes essentially met the intent of the code; no loss of life occurred as the result of structural failure of any modern-code building. However, the earthquake challenged the code's implied objective that buildings should generally resist "a major level of earthquake ground motion . . . without collapse, but possibly with some structural as well as nonstructural damage." At least two notable classes of buildings constructed under modern codes, concrete tilt-ups and steel moment frames, received considerably more than "*some s*tructural damage" and many other buildings that conformed with modern codes,

The best design can be negated by poor construction, and earthquakes have a knack for exposing construction oversights.

Figure 25. Though falling acoustic ceiling tiles like this are not particularly dangerous, falling light fixtures and other heavier elements can be.

though they may not have had severe structural damage, had more than "some nonstructural damage." In addition, parking structures, some built to modern codes, suffered severe collapses.

Moreover, a number of factors may serve to dampen any feelings of elation over the relatively few deaths that occurred:

- Though the shaking in this earthquake was intense, it was the product of a moderate-magnitude, short-duration event. It is reasonable to assume that either a larger magnitude earthquake or one of similar strength but longer duration will subject similar structures to a substantially more strenuous test.
- A number of modern buildings suffered so much structural damage that, had people been in or near them at the time of the earthquake, there would undoubtedly have been much more loss of life. This was particularly true in the case of concrete-frame buildings, tilt-ups, and parking structures.
- Nonstructural hazards and building contents continue to pose a threat to life even in modern buildings (see Figure 25).

To continue down this path of minor code changes makes the task of improving building seismic performance difficult, time consuming, expensive, and only marginally effective.

Seismic Performance Objectives Must Be Clarified

Continuing current practices that have performance goals aimed primarily at protecting life may no longer be appropriate for many building types. The state has a vested interest in the economic protection of the building stock to protect the state's economy and public welfare and to ensure that essential services continue to function after earthquakes.

Though various implied performance objectives or goals for specialized occupancies such as hospitals and essential services buildings set forth in separate laws, there are no clearly defined levels of seismic performance objectives in the current building code. Thus, there are no explicit choices for owners, lenders, insurers, or governmental agencies for more typical engineered buildings or for conventional wood-frame construction. Owners can choose to exceed minimum building code requirements, and engineers can encourage them to consider how slightly increased design and construction costs might reduce damage in future earthquakes, but comprehensive design guidelines to help owners and engineers evaluate these alternatives are not widely available. Such design guidelines are still in their developmental stages, so designs that exceed minimum building code requirements are now the exception rather than the norm. Most owners simply assume the code is good enough or the best that can be done.

Besides improved reliability in meeting the life safety minimum performance objective, many building owners and tenants need enhanced performance objectives that go beyond the life safety minimum to allow for reoccupancy of damaged buildings and resumption of building functions in a timely manner after future earthquakes as well as lower repair costs. Without a framework of widely accepted design guidelines that encourage higher seismic performance objectives, it will be extremely difficult to bring together the financial community, commercial building owners, building designers, and government to provide buildings that will remain functional and suffer less damage after future earthquakes.

The Commission believes the approach to seismic design used in the building code requires significant change. The code's seismic provisions are simplified for ease of enforcement and do not always reflect state-of-the-art knowledge about the dynamic behavior of buildings. The original performance goals and seismic provisions of the code were developed many years ago when the understanding of earthquake shaking and building response was far less sophisticated; today, many of the original underlying assumptions of the code are no longer appropriate. Even though the code is amended after every earthquake, the fundamental approach has not changed. To continue down this path of minor code changes makes the task of improving building seismic performance difficult, time consuming, expensive, and only marginally effective.

Many believe there is a need for performance-based design guidelines in California. Without widespread use of performance objectives that encourage and promote reduction of damage from shaking, the financial risk from earthquakes will continue to increase. The Commission believes the policy of this state must be to encourage and facilitate an environment in which building owners, designers, lenders, insurers, and government (from local to federal) view seismic performance as critical to minimizing economic losses. The state should actively participate in the development of enhanced seismic performance objectives, incentives, and risk-sharing programs that will lead to risk reduction.

Seismic performance objectives for buildings can be raised if measures are taken that go beyond the code. Structures can be designed and constructed to withstand even more intense shaking than seen in the Northridge earthquake with less damage. The knowledge and ability exist, and the incremental cost for new structures is not prohibitive.

Achieving Performance Objectives

New seismic design guidelines can be developed that will achieve different building performance objectives under various levels of shaking. However, it is clearly not possible, and indeed may be dangerous, to attempt to place new seismic performance objectives directly into the existing building code. Instead, future codes should refer to a set of comprehensive design guidelines that offer owners and designers both the flexibility and the tools to meet performance objectives much more reliably than current codes.

Under such a concept, the seismic performance desired for a building could be specified from several available, ranging from a minimally acceptable objective that would ensure life safety, through intermediate objectives providing greater protection against damage, to an objective aimed at providing continuous occupancy and the functioning of essential services after design-level earthquakes. Owners might even be required to disclose seismic performance objectives to prospective buyers of buildings. The use of guidelines would rely heavily on engineering judgment and peer review to ensure that their applications are appropriate.

SEAOC, in its Vision 2000 project, and FEMA are both interested in developing guidelines that would achieve different performance objectives. Given the competing interests involved and the nature and history of code changes, it is reasonable to expect that such a change is not likely to occur until well into the twenty-first century without strong support from such entities as state and local governments and insurance and lending institutions.

There are difficult questions to be resolved, involving such issues as defining performance objectives, providing for variability of actual performance, and addressing owners' and professionals' liability issues and insurance. Perhaps the biggest hurdle is to find cost-effective ways to increase the reliability of building systems so that they will more consistently meet or exceed performance objectives. However, none of those problems are insolvable. The Commission believes that the process of developing more appropriate seismic provisions needs to be given more specific support and direction from government policy makers, owners and operators of essential services buildings, and lending, real estate, and insurance interests.

Without the development of widely used design guidelines for enhanced seismic performance objectives, it will be extremely difficult to develop a rational scheme of creating incentives for owners, lenders, insurance companies, and the government to promote and facilitate the design and construction of many different types of buildings

The first step in developing enhanced seismic performance objectives is to establish a clear policy on acceptable levels of risks.

that will sustain relatively nominal damage in a strong earthquake. Without recognizable and realizable alternatives for seismic performance, lenders, insurance companies, appraisers, and others cannot provide appropriate financial incentives. The Commission believes that now is the time for initiating a process to improve seismic performance objectives for buildings. It is in California's best interest to develop seismic provisions that not only protect public health but also the economic welfare of Californians.

Acceptable Seismic Risk

Buildings built to post-1976 codes essentially met the intent of the code. No loss of life occurred as the result of structural failure of any modern-code building.

Tradeoffs between earthquake risks and higher performance objectives boil down to the questions "How safe do we have to be, and how much are we willing to pay for it?" Bearing in mind that there is no absolute safety from earthquake risks and that payment for such safety as can be ensured is not only in money but in convenience, amenities, and competitiveness, the first step in developing enhanced seismic performance objectives is to establish, at the highest levels of government and the private sector, a clear policy on acceptable levels of earthquake risk. The Commission's *Policy on Acceptable Levels of Risk in State Government Buildings* is a good starting point:

> The goal of this policy is that all state government buildings shall withstand earthquakes to the extent that collapse is precluded, occupants can exit safely, and functions can be resumed or relocated in a timely manner consistent with the need for services after earthquakes. Compliance with this policy will provide reasonable protection of life, but it will not prevent all losses of life, building function, or damage.

The Commission believes that it should convene, with the Governor's assistance regarding participation, a "California Earthquake Risk Colloquium" to weigh the potential benefits and costs of enhancing seismic performance in buildings and provide direction to the developers of future design and construction guidelines. The CBSC should use the results of the "Colloquium" and take steps to implement its recommendations with assistance in testing and applied research from the Center for Earthquake Risk Reduction. The Commission suggests that, as a reasonable goal, the state should support the development of comprehensive building design guidelines so that they are available by the year 2000.

Recommendation

The Commission recommends that:

- The Governor support and participate in a special high-level task force, the "California Earthquake Risk Colloquium," a meeting convened by the Commission to recommend acceptable levels of earthquake risk and performance objectives consistent with those levels.

Testing and Research

The state should immediately begin to correct the practice of relying on unverified technical changes to the building code. However, it will take sustained efforts over many years to solve all the existing problems, let alone those related to future technical developments.

The Commission, in response to a legislative mandate, recently proposed a new Center for Earthquake Risk Reduction. The center would have as its primary responsibility the goal of securing state, federal, and private-sector funding for solving high-priority earthquake problems. In consultation with the CBSC, it should focus first on verifying unsubstantiated code changes as one of the state's most pressing seismic safety needs.

A second, and equally important, objective would be to improve the transfer and use of new technology. A concerted, long-term effort is needed to improve the use of available knowledge in the codes and in the design and construction professions.

Another key goal would be to achieve desired performance for new and existing buildings. This goal includes developing a better understanding of the behavior of building systems, correlating system performance in earthquakes with codes and practices under which they were constructed, and improving quality control, design, construction, and retrofit measures. The new center would address the shortcomings in the current building code.

The authority to create this center exists in the Government Code, but state funds are needed to fulfill the mandate and to influence, focus, and expedite the applied technology efforts within local, state, and federal governments and the building industry. A modest initial state investment of $5 million—one-tenth of 1 percent of the losses in a moderately damaging earthquake—could establish the Center for Earthquake Risk Reduction and fund its initial efforts (SSC, 1994e).

Recommendation

The Commission recommends that:

- Legislation be enacted to authorize funds for a Center for Earthquake Risk Reduction with a sustained funding source to help achieve desired earthquake performance for new and existing buildings.

Need for Response Data

Response data are vital to understanding the behavior of buildings during earthquakes. Unfortunately, many damaged buildings in southern California were not adequately instrumented. For example, only one confirmed set of records was obtained from hundreds of damaged steel buildings.

Prior to 1971, the City of Los Angeles adopted an ordinance requiring building owners to install three strong motion recorders in buildings over nine stories. When the San Fernando earthquake occurred, these instruments yielded an invaluable set of data on ground motion and building response that for many years served as the basis for revisions to building analysis and design. This program became a worldwide model of a successful municipal strong-motion instrumentation program. In 1983, however, the Los Angeles program was modified to require only one instrument per building, located at the rooftop. Following the Northridge earthquake, 490 records were recovered from 300 buildings. Approximately 100 of these records were from older buildings with two or three instruments; the remaining records were from buildings with only one instrument. Data from only one instrument give some indication of the performance of a building but do not permit detailed study of building's response. A much more aggressive program of instrumentation of buildings in California is needed.

"How safe do we have to be, and how much are we willing to pay for it?"

Recommendations

The Commission recommends that:

- The California Strong Motion Instrumentation Program (SMIP) develop a program to encourage all municipalities in Seismic Zone 4 to designate significant buildings in their jurisdictions and to adopt building instrumentation ordinances that require owners of these buildings to install and maintain at least three strong-motion instruments in each.
- SMIP develop and adopt standards for the installation and maintenance of building strong-motion instrumentation and provide for processing, archiving, and disseminating records obtained from buildings instrumented according to these standards.

Reducing Nonstructural Hazards

Structural elements—beams, girders, flooring, roofs—hold buildings up. Nonstructural elements are attached to provide specific functions. Some nonstructural elements—ornamentation and appendages (such as cornices and statuary), chimneys, tanks, signs, storage racks, suspended ceilings, raised access floors, permanent floor-supported cabinets, book stacks more than five feet tall, and electrical or mechanical equipment requiring anchorage—are covered by the building code, but furnishings and most equipment are not (see Figure 27). Building contents are installed by owners without government oversight to ensure their seismic safety.

There are three kinds of risk from nonstructural hazards:

- Risk of injury
- Risk of property loss
- Risk of interruption of function

The Northridge earthquake caused nonstructural property losses estimated in the billions of dollars. Safety was compromised when heavy light fixtures fell and massive pieces of building veneers and ceilings were dislodged, though the early hour that the earthquake occurred reduced fatalities. One insurance company with a $60 million commercial earthquake policy loss found that the majority of the claim was due to only one kind of damage—nonstructural sprinkler pipe failures. The majority of the approximately $300 million in damage to Los Angeles Unified School District facilities was also nonstructural.

The Northridge earthquake caused nonstructural property losses estimated in the billions of dollars.

Interruption of essential functions, such as the failure of backup power generators at fire department dispatch centers (for example, Los Angeles City Fire Department) and hospitals (for example, Los Angeles County's Olive View Medical Center) have life safety consequences. Interruption of business functions, such as corporate data processing centers and unoccupiable industrial, commercial, and residential buildings, can have economic consequences that may exceed the cost to repair and replace damaged elements. In many buildings, damage to the mechanical systems, including heating, ventilating, and air conditioning (HVAC) equipment as shown in Figure 28, resulted in lengthy downtime.

Other nonstructural damage in the Northridge earthquake included:

- *Water leakage* from broken sprinklers and other piping was particularly prominent. Opinions vary as to whether the use of the 1991 edition of NFPA-13, the standard that guides the installation of fire-sprinkler piping including seismic bracing requirements, would have prevented most of this damage. Very few buildings had sprinkler piping installed according to this recent standard, so the earthquake largely tested older standards. Related to sprinkler performance is the behavior of nearby nonstructural components such as suspended ceilings, light fixtures, and ductwork. Most sprinkler failures were caused by flexible suspended ceilings swinging and hitting rigid fire-sprinkler lines. The design professions (especially the architect and the mechanical engineer or specialists such as fire-protection engineers within the mechanical engineering discipline) and subcontractors do not coordinate their work closely enough, so the building ends up with a mixture of nonstructural components that sometimes defeats the earthquake-resisting details of the individual systems. The impact of water leakage that prevented the functioning of hospitals in the region of strong shaking was particularly devastating.
- *Water heaters* toppled in the earthquake, causing damage from water leaks, gas leaks, and fires. Though state laws and the building code require the bracing of newly installed water heaters, many existing water heaters were installed before these laws existed, or they were installed without permits or in violation of the building code. Existing laws also require manufacturers of water heaters to include bracing instructions and warning labels for new heaters, but these laws have not been enforced. Water heaters have also posed risks of injury to occupants who are struck as they topple or when they obstruct exit ways.
- *Elevators* have been subject to retrofit requirements in California for over a decade; October 1982 was the deadline for compliance with Title 8 Elevator Safety Orders of the California Administrative Code. New elevators have been installed with additional earthquake protection features, chiefly a self-shutdown sensor and improved bracing of the heavy counterweights that are used in cable-traction systems. The 1971 San Fernando earthquake was the chief motivation for this upgrading of elevator earthquake regula-

tions. One of the most serious kinds of elevator damage, which can cause injuries as well as lack of service, is derailed counterweights: 674 derailed in the 1971 event, and the number that came out of their guide rails in the Northridge earthquake was almost the same—688. Although the earthquake occurred at 4:31 a.m. when few elevators were in use, a CalOSHA survey of elevator companies found that occupants had to be rescued from 39 elevators.

- *Hazardous material spills* caused by nonstructural damage, such as toppling of contents in laboratories, were documented in detail at the CSU Northridge campus, where chemical spills occurred at over 200 locations. Releases in three of the four science buildings resulted in fires, all in labs where organic solvents were in use. Approximately 50 compressed-gas cylinders were badly damaged in these fires, and another 50 exploded. Few or none of the most likely sources of hazardous material releases in a typical laboratory are covered by the building code, since storage of contents is outside the code's scope. Thus, regardless of improvements in the UBC's nonstructural provisions over the years, hazardous material spills are likely to continue to happen in earthquakes unless other controls and programs dealing with occupants' use of buildings are implemented.
- *Exterior plaster soffits* (exterior ceilings and overhangs) and wall finishes failed in several buildings that are considered modern (see Figure 26 and Figure 67). Under present inspection practices it is difficult to verify that these elements were constructed with adequate anchorage because several installation steps are involved, and detailed inspections of each phase are not a typical building inspection practice. Once in place, verification is even more difficult. Whereas the earthquake bracing of a lightweight suspended ceiling can usually be inspected by removing the acoustic ceiling tiles, the equivalent procedure for stucco or plaster may require destruction of some of the material.
- *Storage racks*, used in retail warehouse-type stores, performed well in some facilities but poorly in others. Heavy contents fell off racks as well (see Figure 29). The difference between acceptable and unacceptable performance appeared to be related to owners' differing policies. Owners of the better-performing racks purchased racks with heavy storage load ratings, loaded them to only about half their capacity, and kept upper-level items shrink-wrapped together in relatively large and stable blocks. Others purchased less sturdy racks, filled their space with heavy contents, and allowed individual items such as 5-gallon paint cans to be stacked on upper levels.
- *Freestanding masonry walls* (concrete-block fences) suffered widespread failures. Four- to six-foot-tall concrete-block fences fell because they were not well engineered; many were obviously built without any inspection. Some had no foundations, some lacked reinforcing, and where reinforcing was used, it was often ineffective. Similar failures occurred in the 1971 San Fernando earthquake. These deficiencies are all solvable when such walls go

Figure 26. Heavy plaster ceilings or soffits can pose serious risks to occupants.

Figure 27. Unsecured tall, heavy furniture can strike or trap occupants. Building owners, managers, and occupants are primarily responsible for securing them.

Lizundia

Figure 28. Broken supports on heating and ventilating equipment can render this equipment useless.

through a building-permit process and either a design professional or standard details are used. Table 23-P of the 1991 UBC prescribes a force factor for masonry or concrete fences over six feet high, but typical zoning regulations keep almost all such walls from exceeding that height and not all local building departments require permits for such walls.

- *Suspended ceiling* performance in the Northridge earthquake was similar to that in other recent California earthquakes. Unbraced or less-than-completely-braced ceilings frequently dropped tiles, and sometimes entire T-bar gridworks were damaged and partially fell. In a department store in Sherman Oaks, part of one floor had been remodeled and the ceiling had been brought up to recent code requirements, which included diagonal tension wires and vertical compression struts and light fixtures with their own vertical support wires. Damage to the older part of the ceiling was extensive, but not one ceiling tile or light fixture from the remodeled section fell during the earthquake, indicating the effectiveness of these features.

EERI

Figure 29. Collapsed storage racks would have posed substantial risks to life had this building been occupied during the earthquake.

- *Storefront window breakage* was common throughout the San Fernando Valley, but it was unusual to find more than a few percent of the windows in large multistory buildings broken. One possible explanation is that typical midrise or highrise buildings benefit from better architectural-engineering attention to the effects of building drift on window assemblies than the typical one- or two-story commercial building receives.

  Breakage of glass often occurs at entries to buildings, a location that maximizes the potential for injuries. Aftershocks are a particular danger with this nonstructural component. The broken panes pictured in Figure 30 were misaligned and some cracked in the main shock at 4:31 a.m., but it was an aftershock that caused the panes to fall out. Figure 31 shows how such buildings are posted with placards, raising the issue of whether nonstructural post-earthquake safety criteria need more emphasis.

The Commission believes that had the earthquake occurred during a normal work or school day, there would have been many deaths and injuries from nonstructural failures. Losses from nonstructural damage were significant, and measures are needed to reduce damage in future earthquakes.

Nonstructural elements should not pose a risk to life. Tenants and owners should be able to better anticipate the amount of damage and length of interruption from such damage. Performance of nonstructural elements has improved over the past several decades, but three major problems remain to be solved:

- Nonstructural components are more vulnerable to damage at low-to-moderate levels of shaking than structural elements. Even at higher levels of shaking, nonstructural property losses may still exceed structural damage because they are so widespread.
- Nonstructural elements receive less detailed architectural and engineering attention and less building-inspection effort to ensure conformance with code requirements than do structural elements.
- The complete “collapse” of a nonstructural element is not always a major threat to life, property, or building function. The specific performance objective, or acceptability criterion, for a nonstructural element in a particular kind of building must be considered (Figure 32).

The Commission believes that nonstructural damage can be mitigated by a series of discrete changes to codes, standards, retrofit policies, and installation practices. For example, the City of Palo Alto requires ceilings, lights, and ducts to be braced during renovations, even if they are not directly a part of renovation (Palo Alto, 1991). In addition, recommendations made in this chapter on quality of design and construction should provide significant improvements in mitigating nonstructural as well as structural vulnerability. The Commission believes that standards for new construction and retrofits need to be developed and made mandatory for such nonstructural building components as fire sprinklers and water piping leak control valves, storefront window assemblies, and emergency power systems.

Recommendations

The Commission recommends that:

- The Division of the State Architect draft nonstructural standards for new construction and retrofits and submit them to the CBSC to be made mandatory by reference in the California Building Code.
- CBSC amend the California Building Code to require a quality assurance plan for all engineered buildings for the design and installation of nonstructural bracing.
- CBSC amend the California Building Code to require the design professional of record to delegate design, coordination, and field review responsibilities for nonstructural building components.
- The Public Utilities Commission work with utilities to develop a program to allow gas utilities to include checks for water heater braces in their routine service calls, to notify building owners if water heaters are not properly braced or equipped with flexible gas lines, and to encourage or require retrofits of water heaters within a reasonable period of time.

Making Existing Buildings Safer

The Commission believes that the greatest seismic risk in California today comes from vulnerable existing buildings. Though only a small proportion of these are likely to have life-threatening failures or collapse in an earthquake, the risk they pose is great. Most of the recommendations in this report call for actions that will reduce the vulnerability of structures not yet built, but changes in tomorrow's building codes and enforcement practices will not reduce the risks associated with existing vulnerable structures.

Only a small percentage of existing buildings are demolished or renovated in any year. The numbers may vary from locale to locale and for different types and uses of buildings, but it is likely that, unless a major urban earthquake occurs, at least 90 percent of the buildings existing in


Reitherman

Figure 30. Large broken windows at a hotel entrance pose major falling hazards.

Reitherman

Figure 31. Typical "green tag" placard used to post buildings as safe to occupy. It states nothing about hazards from nonstructural elements or building contents.


Reitherman

Figure 32. A light fixture partially fell when an anchor for one of its two safety wires pulled out at the Sylmar County (Olive View) Hospital.

California today will still be in use ten years from now—and posing the same threat that they pose today.

Owners have the most to lose in earthquakes and the most to gain from retrofitting.

With each new earthquake, including Northridge, we gain greater understanding of which building types, structural systems, details, and nonstructural elements are particularly hazardous. We know the types of "older" buildings that pose potentially significant life safety risks. The 1976 UBC is often used as the benchmark for identifying older engineered buildings. Many engineered structures built to pre-1976 codes are fine, but some pose unacceptable risks. The 1976 date, generally applicable to engineered structures, is not a valid date for conventional light-frame construction, which includes most homes. Conventional construction is considered "older" if built to codes older than 1949-1960, depending on the jurisdiction.

Alcorn, Los Angeles Times

Figure 33. Both ends of this 1960s medical office building collapsed and the second floor "pancaked." Fortunately it was not occupied.

A number of building types are vulnerable to earthquakes, and in the Northridge earthquake they again demonstrated their potential to collapse and pose significant threats to life and loss of building functions. For example, the concrete columns and beams in buildings erected before the mid-1970s often lack reinforcing steel to keep them from collapsing or being damaged beyond repair in earthquakes. These buildings, like the ones shown in Figure 33, can pose the greatest threat to life in earthquakes because, though there are just a few of these buildings throughout California, they often house large numbers of offices. Just one collapse could cause hundreds of deaths. In the 1971 earthquake, three such hospital buildings in the San Fernando Valley collapsed, killing 52 people. Figures 34 through 37 show other building collapses in the Northridge earthquake.

Building types with a high risk of collapse include nonductile concrete frames, URMs, tilt-up concrete walls, precast and prestressed concrete elements, and inadequately braced, or "soft," first stories. Above-grade concrete parking structures and concrete or steel-frame buildings with URM infill are also commonly regarded as potentially hazardous in earthquakes. Engineers or architects evaluating such buildings may find them unsafe for occupancy.

Unfortunately, little information is available concerning the total number of buildings of various types and their locations to help in planning and carrying out retrofit programs. The experience after the Northridge earthquake shows that there is no systematic collection of information on good or poor performance of the various building systems. Much of the information collected has been anecdotal and thus is likely to be incomplete and biased. Each community should consider developing a database containing information on structural type, age, size, location, and occupancy of each vulnerable building in the community to estimate the number of buildings expected to be damaged in an earthquake and to encourage owners to decide whether their buildings should be retrofitted. In addition, the database would allow for much more realistic use of hazard mapping results and emergency planning scenarios.

Efforts to upgrade or retrofit existing structures pose complex policy and engineering issues including identifying and evaluating specific vulnerable structures, setting priorities for retrofit, establishing uniform retrofit standards and performance objectives or acceptable damage levels, providing appropriate incentives to encourage mitigation, and in some cases mandating action.

It is important to stress that though state and local government will suffer indirect losses caused when private structures are damaged, it is the building owner—public or private—who bears the brunt of the loss and liability for injuries. Owners have the most to lose in earthquakes and the most to gain from retrofitting.

Building owners, whether individuals or companies in the private sector, school and hospital boards, or state or local agencies are responsible for the performance of their buildings. Legal defenses based on not knowing of a structure's vulnerability will fall on deaf ears. A 1985 legal opinion by the Attorney General states that an engineer who determines that there is an imminent risk of serious injury to the occupants of a building and who is advised by the owner that no disclosure or remedial action is intended has a duty to warn the identifiable occupants or, if that is not feasible, to notify the building official or other appropriate authority of such determinations. The state and local governments can help reduce the uncertainties involved in retrofitting or demolition by encouraging planning and providing decision-making methodologies, standards, and incentives.

As difficult as identifying hazardous building types may be, it is relatively easy compared to the more controversial task of deciding which buildings are so vulnerable that retrofit or demolition should be mandated. There are limited data from earthquakes on building performance. In most earthquakes, only the damaged buildings are surveyed, and the lessons on good performance typically go unnoticed. In addition, the use or occupancy category of a building, its age, and its location all play a role in how vulnerable the building may be.

Retrofit Standards

Standards for retrofitting vulnerable structures are not addressed in the building codes, and there is no broad consensus on performance objectives for retrofits or on standards to meet them. However, FEMA is making a major push to develop standards for retrofitting buildings, including varying performance objectives, by funding a five-year, $8 million effort that is being directed by BSSC through the National Institute of Building Sciences. The primary subcontractor for the development of the provisions is ATC, a California-based nonprofit buildings research organization, and the majority of the engineers and researchers working on this project are from California.

Tobin

Figure 34. If buildings such as this had been occupied, hundreds would likely have been killed during the Northridge earthquake. This building was incompletely retrofitted after the 1971 earthquake, which may have hastened its demise in this event.

California already has some experience with these issues. There are both statewide and local programs aimed at reducing the risk from existing structures. The Unreinforced Masonry Law of 1986 provided a backdrop against which many different types of programs can be examined. Apart from mandatory inventory and notification requirements, the URM Law left determination of whether risk mitigation should be required to the local jurisdiction (see Figure 38). Although this provided significant flexibility, it also resulted in a high level of conflict between building owners and local governments. In addition, it created a variety of unequal strengthening programs across the state, resulting in significantly different levels of risk to life and property. Most communities with retrofit programs use some method of establishing retrofit priorities that involves at least occupant exposure and building type and occasionally geological considerations.

The general plan is the local government's policy document for balancing the community's opportunities and problems. Reducing seismic risk from vulnerable existing buildings should be a consideration in these decisions. Each city and county and state agency must decide how to carry out retrofit policies that take into account the availability of funds; local economic, social, and geologic conditions; community values; and seismic risk. The general plan can be an appropriate tool for developing and conveying these policies. For more information and recommendations on land use planning, see Chapter V.

Providing incentives is critical to encourage the retrofit of privately owned buildings. Palo Alto adopted an ordinance that had limited success in encouraging voluntary retrofits; it requires seismic risk evaluation but offers waivers of certain zoning requirements to those who strengthen buildings.

Schmid

Figure 35. Although this retrofitted building lost a few bricks and may be difficult to repair, damage was significantly less than in similar unretrofitted buildings. The outer layer of brick was not adequately connected to the inner layers.

Recommendations

The Commission recommends that:

- Legislation be enacted to require that, by the year 2000, local general plan safety elements contain a generalized description of all typical building types and vintages in the community's neighborhoods, with a special emphasis on those vulnerable to collapse from seismic hazards, and a plan to mitigate the risk from these structures.
- Legislation be enacted to require state and local building code enforcement agencies to identify potentially hazardous buildings and to adopt mandatory mitigation programs by the year 2000 that will significantly reduce unacceptable hazards in buildings by the target year of 2020.
- The Seismic Safety Commission, in conjunction with the California Office of Planning and Research and other interested organizations and agencies, develop guidelines for state and local governments to use to identify potentially hazardous buildings, amend safety elements, and prepare mitigation plans.

Similar efforts and guidelines were undertaken in 1986 for the retrofit of URM buildings in California. These recommendations call for a similar approach for other types of buildings that are known to be hazardous to life.

Retrofitted Buildings

The Northridge earthquake was one of the first earthquakes in which a large number of structures that had been retrofitted for seismic resistance experienced strong shaking. Though the results are difficult to assess with precision, retrofitted buildings typically withstood strong motion better than their unstrengthened contemporaries.

Unreinforced Masonry Buildings

Los Angeles pioneered the retrofit of URM buildings under a program known as Division 88, the city ordinance where it appears. The key objective of Division 88 is to "reduce the risk of life loss." It is not intended to ensure that lives will not be lost, only that the risk will be reduced. Moreover, the performance objectives do not preclude damage so significant that a building might not be economically repairable.

Of the approximately 5,900 retrofitted buildings (most of which were not in the San Fernando Valley region, which was the most heavily shaken), about 400 were damaged in the Northridge earthquake, about 50 so heavily that they had to be demolished. In the City of Los Angeles, 213 retrofitted URM buildings suffered moderate damage and six commercial URM buildings had partial roof collapses (Figure 34). In Glendale, there were 267 retrofitted URM buildings, of which 17 were red-tagged. Burbank had 16 retrofitted URM buildings, of which only one was red-tagged. There was not one loss of life in any of the 1,400 strengthened residential URM buildings (containing 37,000 units) in the City of Los Angeles—most of which were fully occupied at the time of the earthquake—although a significant number of them were in areas of intense, albeit short-duration, shaking.

Damage and partial collapses in unstrengthened URM buildings—particularly in Fillmore and parts of Santa Monica—were noticeably more severe than in similar retrofitted buildings nearby and in other communities. Of the 64 unstrengthened URM buildings in Fillmore, most were severely damaged; many have since been demolished. Clearly the Northridge earthquake reconfirmed that strengthened URM buildings perform better than unstrengthened URM buildings (Figure 36).

Whether the performance of retrofitted buildings for this size earthquake was acceptable remains an open question, but many engineers view the performance of retrofitted buildings in the Northridge earthquake positively. One engineer who helped to develop Division 88 went so far as to call it "an unqualified success" after review of damage following the earthquake (Schmid, 1994b). Another engineer states that "overall, the City of Los Angeles retrofit program (Division 88) must be judged a success in the Northridge earthquake" (Hamburger and McCormick, 1994b). Many others appear to agree and note that no lives were lost and damage to the total stock of retrofitted buildings was significantly lower than damage to similar unretrofitted buildings, such as in Fillmore.

However, some engineers have pointed out that while the percentage of significantly damaged retrofitted URM buildings is small across the entire sample, this is partly because there were few URM buildings in the San Fernando Valley area and north where shaking was greatest. In the isolated pockets where there were retrofitted URM buildings and where shaking was intense, such as West Hollywood and Santa Monica, damage to retrofitted URMs was greater than damage to other buildings. The early-morning occurrence of the earthquake is also believed to be a significant factor; had the event occurred at noon on a work day, when pedestrians were on the street and at risk from collapsed parapets and upper-story wall failures, results and reactions would have been different.

A number of engineers and building officials attribute much of the significant damage to poor design and construction, not to the code itself. Some investigators reported that the damage in retrofitted URMs appeared to be in large part caused by design or plan check errors and lack of adequate quality control, citing numerous instances where unbonded brick veneer was incorrectly used in calculations of wall height-to-thickness ratios. There were also reports of buildings that appeared to have low mortar strength but were assigned much higher values by the original testing laboratory and reports of drawings that did not conform to the buildings being strengthened. In addition to stating that quality control was a more severe problem than the Division 88 standards, a city task force also recommended a number of specific code changes. The fact of the matter remains that URM buildings are brittle, vulnerable structures, and the degree to which seismic improvements can be made is limited by economic feasibility.

Many owners were unaware that a retrofitted building could still be damaged to the point of not being economically repairable. For example, the South Central Southern Missionary Baptist Church spent $250,000 on earthquake reinforcement three years before the earthquake but, following the earthquake, the Reverend J. L. Gates stated, "There is no question we'll have to tear it down" (L.A. Times, 1994). Lula Washington, director of the Los Angeles Contemporary Dance Theatre, whose West Adams Boulevard headquarters was significantly damaged, observed, "When

Figure 36. The entire facade of this unretrofitted brick building in Fillmore was lost. The city contemplated requiring retrofit measures but concluded as recently as 1993 that they were economically prohibitive.

The Northridge earthquake reconfirmed that strengthened URM buildings perform better than unstrengthened URM buildings.

Figure 37. This retrofitted brick building collapsed in part because its wall braces were ineffective.

I saw this building, I almost collapsed myself. We reinforced for over $200,000 in 1992" (L.A. Times, 1994). The distinction between life safety risk reduction and damage control is not well understood by many owners of retrofitted buildings (Figure 37).

In summary, retrofits of URM buildings significantly reduce, though they do not eliminate, the risk to life. However, many owners have obviously not been informed about the limitations of retrofitting. From an investment standpoint, since retrofitted URM buildings clearly may not be functional or economically repairable after moderate earthquakes, owners or potential owners considering retrofits must take the anticipated costs of repair into account, in addition to the immediate costs of the retrofits, when deciding whether to retrofit or replace.

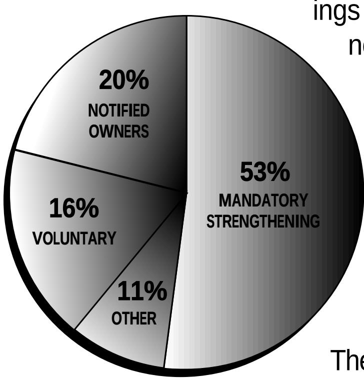


Figure 38. Types of programs instituted by local governments in response to the state's URM Law.

Effects of the URM Law

The URM Law was passed in 1986, requiring that local jurisdictions survey their communities for URM buildings and establish risk-reduction programs that, at a minimum, included notification to the owners that their buildings were potentially hazardous. By 1992:

- 20 percent of the communities had "complied" with the law with ineffective URM programs that only notified the owners and did not require them to take any action (Figure 38).
- About 16 percent had chosen voluntary strengthening programs that were only somewhat more effective in actually reducing earthquake risk. Most URM buildings in these programs remain unstrengthened today.
- About 53 percent of the communities require mandatory retroactive strengthening of URM buildings. This effort has resulted in the strengthening of about 50 percent of the targeted 25,000 buildings and over $2 billion in retrofit expenditures by private and government owners. An additional 15 percent of the buildings (approximately 3,800) are likely to be strengthened in ongoing mandatory strengthening programs between now and the end of the century (Figure 39).
- 11 percent had some other type of program.

In the Northridge earthquake, the mandatory retroactive strengthening efforts of several cities, led by Los Angeles, made a substantial difference. They dramatically reduced damage and life-threatening situations in URM buildings. Voluntary strengthening programs and other URM "risk-mitigation programs" that simply involve the notification of owners that they own potentially hazardous buildings are clearly not effective for risk mitigation. Moreover, such programs essentially violate the Legislature's intent of state-mandated local programs by delaying proactive risk-reduction measures and prolonging undue public exposure to life-threatening buildings.

Fillmore notified its URM owners but never adopted an official URM risk-mitigation program. All owners were notified of the risk posed by their buildings long before the earthquake, and the city council debated the merits and costs of retrofitting. However, because the rents are too low in Fillmore to generate sufficient funds for major capital outlays in many of these buildings, Fillmore in 1993 reluctantly chose to forego efforts to reduce seismic risk in their buildings. Mr. Roy Harthorn, Santa Barbara's building official, who assisted the city staff in evaluating

Fillmore's seismic risk, described the situation as follows:

> The city council faced a dilemma of choosing either an overly burdensome mandatory program with effective measures that economically would not materialize, or to enact a voluntary program that would lack sufficient impetus to be effective. I interjected that there was considerable middle ground to consider such as longer term deadlines in the 10 to 20 year range, property resale trigger mechanisms, re-roof trigger mechanisms and other less burdensome trigger mechanisms designed to minimize fiscal impacts on the property owners (Harthorn, 1992).

This same scenario has occurred in numerous other cities such as Whittier, Pomona, Oakland, Santa Cruz, Watsonville, Hollister, and Coalinga.

Existing state laws also encourage limited disclosure of general seismic safety information at the time of sale of all commercial buildings. State law also requires owners to place placards warning the public about earthquake risk at the main entrances to URM buildings. However, no government agency is responsible for enforcing these laws, so compliance is spotty at best. Even if governments required a formal disclosure of seismic risk that included a clarification of the benefits and limitations of retrofitting, most building owners are still not equipped to understand or manage their seismic risk in any comprehensive way.

Seismic risk has greatly reduced the market value of unstrengthened URM buildings, but rental rates are still controlled by local market rates. Therefore, private owners of URM buildings typically have difficulty securing loans for seismic retrofits and are unable to raise rents to establish a source of revenue to pay off retrofit costs without losing tenants. Some local government owners have established bond programs to finance retrofits of their own buildings, but very few local governments have created financial, land use, and zoning incentives for seismic retrofits of private buildings, although state laws have recently been changed to make it easier to create programs such as assessment districts.

Recommendation

The Commission recommends that:

- The Legislature revisit the state's 1986 URM Law and consider appropriate actions to address the inequities and the public's continuing exposure to risk that have resulted from the failure of a significant number of local governments to comply with the intent of the law so that approximately half of the state's URM buildings remain unstrengthened.

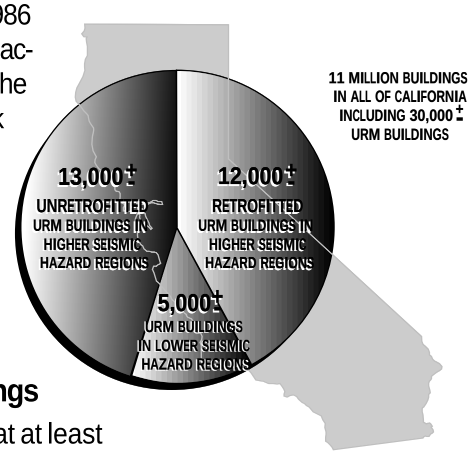


Figure 39. Approximate numbers of URM buildings, retrofitted and unretrofitted, in California.

Other Types of Retrofitted Buildings

Preliminary information indicates that at least five retrofitted nonductile concrete-frame buildings performed adequately: three in Los Angeles, one in Santa Clarita, and one in Topanga Canyon.

- The three buildings in Los Angeles, all located on the UCLA campus, are seven-story student residence halls originally constructed in the early 1960s. A structural evaluation in 1981 indicated several hazards in the structures, including a potential column shear failure, a lack of confinement in the columns, a potential strong-beam, weak-column mechanism, and potential column damage under the discontinuous walls. The retrofit involved concrete jacketing the concrete moment-frame columns and lower-level spandrels and adding new concrete walls below the discontinuous walls or strengthening the columns below those walls. All three buildings performed well with only minor damage, but the shaking from the Northridge earthquake was estimated to be a relatively weak 0.15-0.20g at that site.
- The Santa Clarita building is a two-story commercial building with post-tensioned concrete flat-slab floor and roof and 30-inch-square concrete columns that originally relied on flat-slab moment-frame

EQE

Figure 40. This building in Santa Clarita is shown during its 1993 retrofit which was undertaken with minimal disruption to its occupants. The building emerged from the Northridge earthquake with no structural damage.

Most building owners are still not equipped to understand or manage their seismic risk in any comprehensive way.

behavior for lateral resistance. The building was strengthened in 1991 by adding new concrete beams above the floors in selected locations to form frames. These beams were designed to cause yielding in the new beams rather than the existing columns. The retrofit design was based on the 1988 UBC. This building experienced intense shaking with remarkably little damage (Figure 40).

- The Broadway Store at Topanga Plaza, a retrofitted concrete-wall building located a little over four miles from the epicenter, is a three-story building with waffle-slab floors and was originally constructed around 1964. A 1989 structural evaluation indicated a potential weak story at the ground level, and two shotcrete walls were added at the ground floor. The building suffered significant cracking to both the original concrete and the added shotcrete walls at the first floor as well as significant damage to the adjacent concrete columns. The mechanical penthouse and roof screens were also significantly damaged. Lack of preparation of construction joints in the original walls appears to have contributed to this damage.

A retrofitted concrete-wall industrial building located three miles from the earthquake epicenter fared better. This eight-story building was constructed in 1953 and conservatively retrofitted in 1989 by thickening some existing walls and adding new walls. Nearby ground motion records indicated relatively moderate levels of ground shaking. Following the earthquake, the only observed damage was some minor to moderate cracking in the walls, about the amount expected by the designer and owner for this level of shaking. The building was tagged green.

Only one example of a retrofitted wood-frame apartment complex is known to exist in the region of intense shaking. The building is a three-story, 200-unit complex with tuck-under parking located in Sylmar, approximately seven miles from the epicenter. It was originally built about 1963 with gypsum wallboard and gypsum lath-and-plaster wall cladding providing the lateral force resistance in the upper levels in the longitudinal direction and at the ground level. Several diagonally sheathed walls provided lateral resistance at the ground level but only in the transverse direction. All ground level walls were extensively damaged in the 1971 earthquake. The building was strengthened with plywood walls at the ground level following the 1971 earthquake. Observations following the Northridge earthquake indicate that it performed well, with little structural damage (figures 41 and 42).

The Northridge earthquake reconfirmed observations from past earthquakes regarding buildings with incomplete retrofits. If force paths through such buildings are left incomplete or improperly detailed, the potential for collapse can actually be greater than for unstrengthened buildings. For example, the Bullock's building in the Northridge shopping mall was partially retrofitted shortly after the 1971 San Fernando earthquake, but the added walls were not actually connected to columns as required by the retrofit plans, making the walls discontinuous, which probably exacerbated the collapse of three levels of concrete. The lesson here is that extra care must be taken in retrofitting to ensure complete load paths, attention to details, and integrity of vertical load carrying systems.

Although there were retrofitted structures that suffered significant damage and even collapse, the performance of retrofitted structures including significantly reduced damage, deaths, and injuries in the Northridge earthquake was, on the whole, successful. In those instances where the performance was lacking, quality concerns in either design or construction were noted. A lack of quality is not acceptable for any construction activity, retrofit or otherwise.

Recommendations

The Commission recommends that:

- Legislation be enacted to require owners of potentially hazardous buildings to disclose seismic risk to potential buyers at the time of sale, to lenders, and to tenants on entering into or renewing leases, or when they relocate within a building.

  The disclosure should include pertinent information about the risks of damage, ways to reduce risk and the benefits, costs, and limitations of seismic retrofits.

- Legislation be enacted to allow the warning placards required by existing law to be removed from potentially hazardous buildings that have been retrofitted in substantial compliance with the Uniform Code for Building Conservation, Appendix Chapter 1, provided that the disclosures in the preceding recommendation take place.
- Legislation be enacted to require owners and business operators to include warning placards at the entrances to hazardous buildings of all types as well as seismic risk management and response plans as part of their overall emergency plans for safety in the workplace.
- The Governor direct CalOSHA to inspect, cite, and fine employers and operators when these earthquake warning placards and plans are not present during inspections of workplaces.

Issues for Specific Building Types

Quality control, building codes, nonstructural hazards, and the other issues addressed so far in this chapter apply to virtually all types of buildings. Discussed below are some issues that relate primarily to one or only a few types of buildings or building uses.

Mendes

Figure 41. Damage from the 1971 earthquake in this apartment was similar to damage in the 17 ghost towns created by the Northridge earthquake.

Single-Family Dwellings

In general, single-family dwellings are the safest type of building to be in during earthquakes, but old or poorly built or maintained homes are vulnerable to damage. These present a substantial economic risk to Californians.

Mendes

Figure 42. Walls in this building were repaired and retrofitted with plywood after 1971. In 1994 it suffered only minor damage.

Tens of thousands of one-story single-family wood-frame houses were damaged in the Northridge earthquake. However, a study performed for the Department of Housing and Urban Development that analyzed a random sample of several hundred wood-frame structures within a ten-mile radius of the epicenter found that single-family detached properties had remarkably low levels of serious damage: 90 percent of the structures had no foundation damage, 98 percent had no wall-framing damage, and 99 percent had no roof-framing damage. Nevertheless, over 19,000 single-family homes suffered damage in excess of $10,000 (Comerio, 1995) in the County of Los Angeles alone, and of those about 1,900 still remained vacant in September of 1994. In addition, 10,000 single-family homes had losses from $5,000 to $10,000 (LAHD, 1994).


Russell

Figure 43. This home was retrofitted just prior to the earthquake and sustained far less damage than similar, unretrofitted homes in the neighborhood.

Typical structural damage in single-family homes was not spectacular or life-threatening. It consisted of cracked stucco, walls cracked at garage door openings and at narrow first floor sections of walls, fallen roof tiles, and stucco cracking at the foundation line. Interior damage to gypsum board, finishes, and contents was also common; many chimneys fell; and a few hillside homes collapsed or partially collapsed. Some foundation cracking and settlement was noted, especially in older homes. Even though most of this damage sounds minor, repair costs exceeding $100,000 are not uncommon.

If left incomplete or improperly detailed, a "strengthened" building can be more likely to collapse than an unstrengthened one.

Homes will always suffer some damage from shaking as intense as the Northridge earthquake. Cracking and minor damage cannot be reasonably avoided, but major damage, life-threatening failures, and loss of habitability can (figures 43 and 44). Homes are vulnerable because their design balances seismic resistance with the attractiveness of the home and the cost of construction. The safest building style—a simple one-story wood box on a level lot with only a few small windows and doors—would not be very attractive. The features that make homes more attractive and functional—steeply sloping lots, second stories, split levels, high ceilings, sliding glass doors, and large windows—also increase vulnerability to earthquake damage. Most homeowners would no doubt be willing to risk some earthquake damage, including significant amounts of minor damage, to balance architectural amenities with earthquake safety as long as homes remain habitable.

Building codes are intended to save lives but not to prevent all damage. With the exception of the failures of homes on steep lots in which three persons lost their lives, the safety and health aspect of this intent language was essentially met in the Northridge earthquake. Determining a level of non-life-threatening damage that would be acceptable for a single-family residence is difficult. Views will differ before and after damaging earthquakes and are highly dependent on the perspective of the person asking the question.

A clear public policy statement on acceptable levels of risk in dwellings has never been made in California by the Legislature or any administrative agency. In Chapter VI, the Commission recommends that the Governor support an ad hoc "California Earthquake Risk Colloquium" convened by the Commission to develop a policy on acceptable levels of risk. The Commission believes that an appropriate goal for acceptable performance for new residences should be that:

- Substantial life safety is provided by building elements regulated by the building code (which excludes furniture and contents).
- At worst, the extent of damage is such that residences can be occupied after inspection.

The 1994 UBC changes for conventional light-frame construction, which include a tightened definition of that term, will go into effect in California jurisdictions in July 1995. These amendments are essentially sound and, with minor adjustments that are currently being considered, should protect properly constructed new homes from excessive levels of earthquake damage. However, if a building does not comply with the code, its earthquake resistance may be severely affected.

Building owners are ultimately responsible for complying with codes, yet they generally rely on designers, builders, and building officials to meet them. Local government building officials are responsible for enforcing the building code provisions through plan review and construction in-

CONVENTIONAL CONSTRUCTION

There is an important distinction between conventional light-frame construction ("conventional construction") and most other buildings. Conventional light-frame construction includes light wood-frame buildings of not more than two stories and a basement with four or fewer dwelling units and covers almost all single-family and many multifamily residences. Though conventional buildings, like other structures, are required to be built according to code, they do not need to be designed by an engineer or architect who is trained to calculate earthquake forces and to design lateral force resisting systems. Plans can be drawn by anyone: owners, building contractors, or designers.

spection. For conventional construction, this is meant to ensure that the plans meet the prescriptive requirements of the code and to ensure that builders adhere to the plans, use appropriate materials, and follow accepted practice during construction. Though many building departments have tried to get by with limited reviews of residential construction, "spot checks" by building inspectors clearly do not provide sufficient assurance or reliability that new construction will comply with the code and provide adequate seismic safety.

A number of quality concerns surfaced in the aftermath of the Northridge earthquake. Although statistically rigorous data are not available to establish even rough percentages of damage resulting from a lack of code conformance, there is ample evidence that failure to follow code requirements in design and lax plan review, construction inspection, and shoddy construction resulted in significant damage in conventional homes. Improperly installed wire mesh that underlay rather than being embedded in stucco, overdriven nails in plywood, nails placed too close to the plywood edges, undersized nails, oversized bolt holes, and improperly placed foundation anchor bolts are examples.

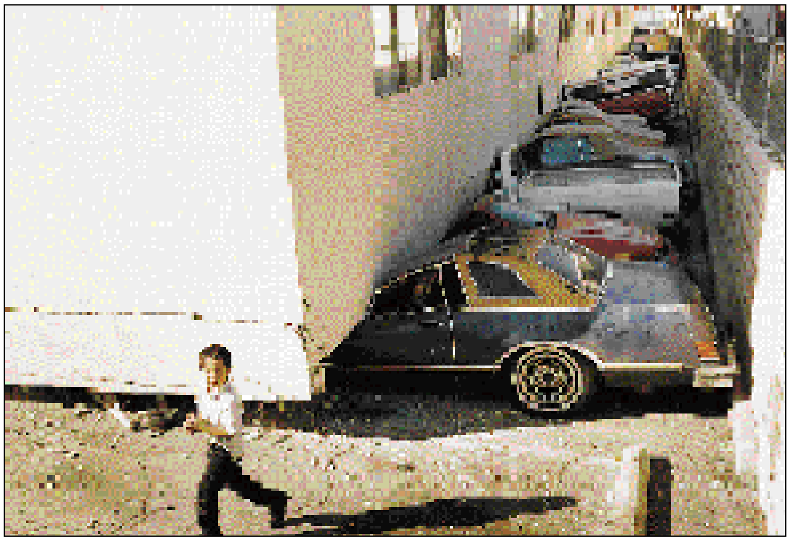
Controlling earthquake damage depends on the integrity and continuity of the building elements that resist shaking. Braced wall panels intended to resist lateral forces generated during earthquakes can be identified on the plans by the owner, contractor, or designer so their integrity can be ensured. The Commission believes that steps to focus on the quality and integrity of braced wall panels will result in improved performance. Requiring builders to designate them on plans, the plan checker to check them, and the construction inspector to inspect each panel will go a long way to improving seismic performance.

Although public K-14 schools are not conventional construction since they are engineered structures designed by registered professionals, a noticeably higher level of performance is achieved because of their enhanced quality of construction. The dramatic differences between public schools and most other classes of buildings is in the plan review and amount of inspection and review during construction. Relatively few of the quality problems that were seen in damaged conventional construction were seen in public schools following the Northridge earthquake.

OES

Figure 44. Older homes with horizontal wood siding are particularly vulnerable to damage if they are not securely fastened to a proper foundation.

Although improvements in the code and in quality control will reduce the vulnerability of new homes, without effective retrofit programs many existing homes will remain vulnerable. Many homes that were seismically retrofitted before the Northridge earthquake suffered significantly less damage than neighboring homes. Efforts to anchor walls to foundations and brace cripple



Otero, Los Angeles Times

Figure 45. Older apartments like this with tuck-under parking collapsed because they were poorly braced.

walls in crawl spaces below first floors seemed to pay off. Cost-effective retrofit programs with information on what should be done coupled with incentives to accomplish the retrofits are essential to any strategy to reduce the vulnerability of older single-family homes to earthquake damage.

Recommendations

The Commission recommends that:

- CBSC amend the administrative portions of the codes to require persons drawing plans for conventional light-frame construction to clearly identify on the building's plans all braced wall lines, wall panels, and their connections.
- Plan checkers be required to indicate that the braced wall lines and panels meet the requirements of the code, and construction inspectors be required to conduct an inspection to ensure that seismic elements are constructed in accordance with the plans and the building code.
- Inspectors receive special training, continuing education, and certification in the basic concepts of structural design in lowrise buildings, the identification and importance of key seismic elements, and the proper installation of materials, hardware, and devices used to provide seismic resistance.
- Banks and insurance companies create incentives to encourage seismic retrofit by offering lower rates on homes that have been retrofitted.

The features that make homes more attractive and functional—steeply sloping lots, second stories, split levels, high ceilings, sliding glass doors, and large windows—also increase vulnerability to earthquake damage.

The Commission is not recommending that builders, plan checkers, and inspectors of single-family dwellings and other conventional light-frame construction do considerably more but that they do it more carefully. Relatively simple changes in current practice will not increase costs in any substantial way, but improving the quality of plans, plan review, construction, and inspection are far more cost-effective ways to improve a building's earthquake performance than across-the-board requirements for increases in the strength of buildings.

Other Wood-Frame Buildings

The vast majority of buildings subjected to the earthquake were of wood-frame construction. As a class, they generally withstood the earthquake without collapse and for the most part without extensive structural damage. However, a subset of wood-frame structures—multistory buildings with "soft," or inadequately braced, lower stories (generally resulting from inadequate amounts of solid wall to resist earthquake motion)—suffered many failures. The collapse of the three-story Northridge Meadows apartment building resulted in the loss of 16 lives.

In the City of Los Angeles alone, over 17,400 multifamily units were vacated, and 13,600 units suffered major damage in excess of $10,000 each. As of September 1994, 210 apartment buildings and 43 condominiums remained vacant in 17 "ghost towns" scattered throughout the city, and 27 buildings with 475 units had been demolished, according to the City of Los Angeles' Department of Housing (LAHD, 1994). The estimated direct loss in single-family and multifamily housing in the City of Los Angeles alone exceeded $1.15 billion as of November 1994. This damage triggered over 200,000 Small Business Administration loan applications, of which only 55 percent had been approved.

Many of these structures experienced either collapse of the first story or horizontal deflections serious enough to preclude economical repair (figures 45 and 46). There was extensive cracking of interior wall finishes and exterior plaster or stucco on wood-frame structures throughout the area. In many buildings, these finish materials also served as structural elements for the resistance of lateral forces, so the damage not only caused cosmetic distress but compromised the seismic resistance of the structure. When a stucco wall is erected, it is backed with a wire mesh over building paper attached to wood stud framing. In many cases, wire mesh was improperly installed, so tight to the building paper that the stucco could not bond to the wire. This problem can be addressed by enhanced quality control and education of contractors, stucco installers, and inspectors.

> Prior to the Northridge earthquake, many multifamily rental property owners had already been overleveraged due in part to Los Angeles' weak rental market. The earthquake severely aggravated financial problems for owners already suffering from declining income and high debt, compounded by the fact that many had no insurance. Hence, with many buildings being damaged and/or vacated, property owners simply do not have the cash flow to meet their continuing obligation toward mortgage payments and taxes (LAHD, 1994).

Many multifamily buildings that were safe to occupy and not significantly damaged structurally still needed repairs. Nonstructural damage was much more extensive—and expensive to repair—than most people would have anticipated. However, the Commission believes that, since occupancy was not interrupted for excessive periods of time and repairs did not have to commence immediately, this level of damage, though a hardship to many, was an acceptable loss.

California's cities and counties have many of the most qualified building departments in the world. Enforcement of design requirements for wood-frame buildings by governmental agencies has increased over the years. However, observations after the Northridge earthquake, as well as recent litigation regarding residential construction defects in California, reveal that many of the requirements of the building codes are being overlooked or inadequately enforced. Features and requirements of the approved plans are not being followed consistently in the construction process. This lack of code compliance is especially significant as it relates to the requirements for the lateral force resisting systems. Substitution of smaller nails and missing or poorly installed structural hardware such as straps, anchor bolts, and holdown devices were found in post-construction inspections. In a 1993 survey of residential and commercial wood construction, G. G. Schierle found that 17 of 28 seismic elements surveyed were missing or flawed in 40 percent of his 135 surveyed buildings. He emphasized, "It is alarming that key items to resist seismic force are among those most frequently missing or flawed" (Schierle, 1993).

Los Angeles Times

Figure 46. Damage to apartments caused more life and housing losses than other building types in this earthquake.

A clear public policy statement on acceptable levels of risk in dwellings has never been made in California by the Legislature or any administrative agency.

Requiring the building designer to observe important details during construction can also improve the reliability of construction. A civil or structural engineer or architect is involved in most multiunit residential projects and virtually all wood-frame commercial and industrial projects but seldom observes construction because it is not typically required by the code and owners are unwilling to pay extra for that service. Moreover, since architects and engineers can be exposed to construction-related disputes

The Commission is not recommending that builders, plan checkers, and inspectors do more but that they do it more carefully.

when present on the job site, many design professionals avoid it, so major design and construction substitutions or changes that affect seismic safety are quite often made during construction.

Recommendations

The Commission recommends that:

- CBSC amend the administrative portions of the codes in California to require professionals who are drawing plans for engineered portions of buildings to include and clearly identify on those plans all vertical and horizontal elements of lateral force resisting systems and their connections.
- Local governments initiate efforts to reduce the seismic risk in vulnerable wood-frame buildings such as collapse-risk apartment buildings with "soft" stories.

Manufactured Housing

As in every recent earthquake, damage to manufactured housing, or mobile homes, was all too common. Numerous studies have found that the performance of mobile homes in California earthquakes is significantly worse than that of conventional wood-frame dwellings.

Because of their light weight, closely spaced walls, and the requirement that they withstand the trailer ride from factory to site without damage, the mobile home itself has been generally regarded by engineers as roughly equivalent in earthquake resistance to conventional wood-frame construction. The federal Department of Housing and Urban Development regulates all manufactured parts of mobile homes above their chassis. With the exception of toppled water heaters and broken gas lines, the seismic performance of mobile homes above their chassis were similar to, if not better than, conventional, single-family wood-frame residences.

MOBILE HOME DAMAGE	
Number of mobile home parks affected	69
Number of mobile homes in affected parks	9,095
Number of mobile homes in affected parks that fell off jackstands or shifted to the point they required reinstallation	5,412
Number of mobile homes that burned	172
Nearly 60 percent of affected mobile homes fell off their foundations (King, 1994).	

The primary seismic weaknesses in mobile homes are the foundations on which the homes are placed. Mobile homes are generally installed on jacks or other supports without regard to wind or seismic forces. These are supposed to be state-regulated and enforced by either the state's Department of Housing and Community Development (HCD) or local governments. However, at the time of the Northridge earthquake, state regulations for mobile home installations were notoriously weak. Although recent legislation applicable to new installations will begin to change this, existing mobile homes remain vulnerable.

Earthquake-activated shut-off valves would probably have prevented some of the fires. However, according to HCD, some of the mobile homes that burned had shifted several feet and severed their gas lines, so individual earthquake-activated gas shut-off valves at the homes would not have prevented these fires. Fires also were started when water heaters toppled and severed their gas lines. Redesigning the gas connections for individual mobile homes to reduce the chance of breakage and installing master shut-off valves that cut off the gas flow at park entrances will reduce the risk of fire. Figure 47 depicts fire damage to mobile homes.

Earthquake resistant bracing (ERB) systems and other techniques can keep mobile homes from shifting off their foundations in earthquakes. A very small number of mobile homes had these bracing systems installed at the time of the Northridge earthquake.

The study of Northridge earthquake mobile home damage by the National Conference of States on Building Codes and Standards found that ERB systems typically kept mobile homes from dropping more than two inches and reduced the horizontal movement. "Damage to units with ERB systems appeared to be less severe than damage to units that did not have ERB systems and that, consequently, were knocked to the ground" (NCSBCS, 1994). HCD estimated that a typical repair cost for a 24-by-60-foot unit is $17,400. Though relatively low compared to other damage figures, it is significant as mobile homes are extremely low-cost housing units in many areas and often sell for a similar amount. The average damage cost is significantly higher than average costs for ERB systems, which range from $750 to $3,000.

According to HCD's case-study letter report on mobile homes, "The earthquake bracing systems that were in place at the time of the earthquake were systems that would not be approved under recently enhanced standards. Many of these systems were not certified or installed under permit since they predate the permit and inspection requirements. Where homes were fitted with approved systems, the systems performed as designed and prevented the homes from falling to the ground. There was still damage to the contents of the homes that moved laterally. In at least two homes, the earthquake bracing systems caused such serious damage to the steel chassis that the homes were 'totaled' by the insurance companies" (King, 1994). Data on the performance of bracing systems in eight mobile home parks indicate that two of nine systems performed well; the other seven were somewhat helpful but had design inadequacies or were not properly installed.

HCD has been certifying products as complying with an HCD standard for ERB systems since September 1985 and, since January 1990, has performed site inspections when these products are installed. A system is not required for either a newly installed or existing mobile home, but if an owner chooses to purchase one of the approximately 20 different systems available, it must be installed to meet the HCD standard. There is less consensus concerning engineering techniques for mobile home foundations than for wood-frame dwellings. Nevertheless, most engineers would generally agree that "properly designed [ERB systems] can enhance resistance to ground motions, and help to prevent the toppling of manufactured housing units in an earthquake" (Pearson et al., 1993).

MOBILE HOME FIRES

CAUSE OF FIRES	% FIRES
Mobile home shifted several feet and sheared off utility lines where they came out of the ground	76
Gas-fired water heater	17
Miscellaneous or unknown	7

HCD Earthquake Response Report *tabulated these statistics from a survey of mobile home parks in the most heavily shaken area (King, 1994).*

From a life safety standpoint, the poor performance of supports for mobile homes poses a danger greater than wood-frame dwellings, but not as great as some other kinds of construction such as URM buildings. Mobile homes do not collapse when thrown off their supports; occupants receive a violent but not usually life-threatening ride. However, injuries can be expected to be higher in unbraced mobile homes than in conventional wood-frame dwellings because occupants and contents are thrown about, and occasionally the steel jackstands penetrate the floor (see Figure 48). Exit doors in mobile homes can also become stuck closed, creating a serious threat to life in the all-too-likely event of post-earthquake fire.

As of July 1994, Governor Wilson had signed Senate Bill 750 (Roberti) which requires support attachments and tiedowns on new installations. Under this new law, HCD also will develop a standard for connecting concrete block

Scawthorn

Figure 47. One hundred seventy-two mobile homes burned in this earthquake. Fires most often started because of severed gas lines.


McGavin

Figure 48. A steel jackstand pokes up through the floor of a mobile home after it shifted.

supports to the mobile homes. The standards will not require the use of ERB systems but will require tiedowns. HCD adopted emergency regulations in response to Senate Bill 750, but recent emergency regulations do not specify mobile home supports adequate to resist earthquake forces, and HCD is now considering revisions.

In summary, the present mobile home installation policy of the state, though recently enhanced, still accepts more risk for the mobile home than for the conventional wood-frame dwelling. The greatest problem remains with the stock of existing mobile homes, which are still not required to be attached to foundations.

Recommendation

The Commission recommends that:

- Legislation be enacted to require the installation of HCD-approved ERB systems or other systems allowed by SB 750 (Roberti) on existing mobile homes when ownerships are changed or when homes are relocated.

Other recommendations relating to mobile homes, including those dealing with gas shut-off valves, are contained in Chapter IV.

Tilt-up and Reinforced Masonry Buildings

The Northridge earthquake caused significant damage to tilt-up and masonry buildings. Tilt-up damage posed potentially life-threatening collapses that had billion-dollar economic implications. The City of Los Angeles estimates that of the 2,000 tilt-up buildings in the San Fernando Valley, over 350 had moderate structural damage and 200 had severe damage with partial roof collapse and collapse of exterior walls. Heavy damage occurred in areas of strong shaking, including Northridge, Chatsworth, Sylmar, and Sherman Oaks as well as more distant areas such as Newhall and Valencia to the north and Santa Monica to the south. For three to six months after the earthquake, about 500 one-story commercial buildings were vacant and as of November 1, 1994, about 200 remained vacant, creating commercial "ghost towns" largely of tilt-up and reinforced masonry buildings (Figure 49).

Tilt-up buildings serve as light industrial and commercial buildings throughout the state. Southern California alone has an estimated 20,000 tilt-up buildings. The concrete walls in tilt-up buildings are poured on the ground slab and, after curing, are raised—tilted up—to their vertical position. Wood or metal roofs are connected to the walls to brace them and help resist earthquakes. The structural characteristics of tilt-up concrete buildings are similar to those of reinforced masonry-wall construction. Both building types are typically one story, are used primarily for industrial or commercial functions, and have flexible roofs and similar roof-to-wall connections. They also perform very much alike in earthquakes.

The first major test of tilt-up and reinforced masonry construction with flexible roofs was the 1971 San Fernando earthquake. Roof-to-wall connections performed poorly: roofs separated from walls, resulting in numerous instances of partial collapse. This damage was repeated in the 1983 Coalinga and 1987 Whittier earthquakes.

One of the more comprehensive reviews of the San Fernando earthquake damage was the 13 case studies in the 1973 National Oceanic and Atmospheric Administration report. Several of the recommendations that resulted from those case studies are interesting because of their relevance 21 years later:

> The connection between the roof diaphragm and the walls should be improved. Criteria should be developed to provide realistic design force and detail requirements for connecting these elements. Some ductility in the behavior of these connections would be desirable to avoid 'brittle' failures. Details should be subjected to realistic simulated earthquake forces prior to approval.

> Stronger connections between main girders and supporting pilasters are recommended. Improvement in the containment of masonry and concrete at the tops of wall pilasters should be studied.
>
> Continuity should be provided completely across the building by tying together the purlins, joists, or other members in addition to the plywood sheathing (NOAA/EERI, 1973).

Partly as a result of these recommendations, the 1973 UBC contained substantial changes in the requirements for new tilt-up and reinforced masonry construction, which were later extended and clarified in the 1976 UBC (Figure 50).

The 1987 Whittier earthquake confirmed that the new requirements improved building performance. A survey of 121 tilt-ups found that code changes adopted to mitigate wall anchorage and diaphragm continuity problems identified in 1971 appeared to be effective for the level of shaking experienced in the Whittier event but identified new vulnerabilities, partly reflecting changes in construction practice, primarily in the detailing of and connections between tilt-up panels. It was believed that code changes resulting from the 1987 Whittier and 1989 Loma Prieta earthquakes had generally solved those difficulties, but the poor performance of tilt-ups in the Northridge earthquake indicates that additional code changes are needed.

Investigators of the Northridge earthquake damage to tilt-ups point out that:

> While no lives were lost as a result of this performance, the damage sustained by many of the buildings was clearly life-threatening. Economic losses relating directly to repair costs, as well as damaged inventories and business interruption exceeds 1 billion dollars (Hamburger and McCormick, 1994a).

In the Northridge earthquake it was estimated that about 40 percent of the pre-1973/76 and 25 percent of the post-1973/76 tilt-up and masonry buildings had roof connection failures. The Earthquake Engineering Research Institute found evidence that "impact from storage racks appears to have accelerated the separation of wall panels from the roof diaphragm." Retrofitted pre-1976 buildings performed better than their nonretrofitted counterparts (Brooks, 1994; EERI, 1994b).

Many tilt-up failures demonstrate the need for actions recommended earlier in this chapter:

- Many damaged buildings demonstrated poor detailing and installation practices.
- Code requirements may need changes to allow for intense shaking. These changes can be made to the existing code through the normal process.
- The allowable values provided by wood-hardware catalogues and ICBO evaluation reports do not appear to be well coordinated with the strength, toughness, ductility, and displacement requirements assumed by code writers, and, in many cases, qualification tests do not accurately reflect field conditions or dynamic forces, according to the Los Angeles Task Force and others. There are also serious concerns about the test procedures, as well as the safety factors being used by the hardware manufacturers.

A potentially more intractable problem is that the displacement or elongation inherent in metal connections may be incompatible with the re-

Tobin

Figure 49. Damage to both new and older tilt-up buildings was widespread.

EERI

Figure 50. Despite changes to the building code made shortly after the 1971 earthquake, failures occurred in tilt-up buildings.

Schmid

Figure 51. This metal connector stretched, distorted, and eventually caused the wood to split.

mainder of the structural system. Hardware catalogs and ICBO reports generally do not provide information about how connections will stretch or deform under earthquake forces, and there is controversy over how much elongation to allow in proposed code revisions. This is a complicated problem that is inherent in the current system of divided responsibility for the various elements of a building discussed earlier in this chapter. In this case, though hardware engineers are responsible for the seismic safety of connection hardware, building engineers are typically not aware of the limitations assumed by hardware engineers. Similarly, hardware engineers may not realize what design assumptions are made by building engineers. Published evaluation reports for connection hardware are based on proprietary test data submitted to ICBO by manufacturers, which is not generally available to building engineers. To improve this system, closer coordination regarding the requirements for acceptability is needed between code writers, manufacturers, and building code enforcement agencies. Moreover, individual elements need to be tested in the context of the full assembly to get proper values. ICBO should also inform design professionals of the limits and assumptions associated with ICBO's product approvals (Figure 51).

Figure 52. Connections between the roof and floor slabs and the columns failed in this collapsed building.

EERI

The Commission believes that the performance of tilt-up buildings as demonstrated by the Northridge and earlier earthquakes needs to be improved. Tilt-up structures provide a large part of the commercial and light industrial base for California businesses. The threat of widespread economic losses and business and industry disruptions in future earthquakes rivals the threat to life.

Recommendation

The Commission recommends that:

- The ICBO Evaluation Service review the building product evaluation and approval procedures used to establish allowable design values for earthquake resistance.

  In light of the poor performance of many ICBO-approved products in the Northridge earthquake, the ICBO Evaluation Service should make comprehensive recommendations on how to change product approval procedures and to enhance descriptions of the limitations and assumptions of the approvals in ICBO's evaluation reports.

Concrete-Frame Buildings

More than any other building type, concrete-frame buildings pose a threat to life in future earthquakes. The performance of concrete buildings in the Northridge earthquake was essentially a repeat of past earthquakes. The unsatisfactory performance of older concrete-frame buildings has been known for over 25 years. But these buildings are hard to identify and evaluate, and not all older concrete frames pose significant collapse threats.

Nevertheless, the obvious question has to be addressed: why has it taken governments and the real estate, insurance, financing, and building industries so long to do so little about reducing the seismic risk in this type of building? This is an example of the lack of accountability to address seismic safety at all levels of government.

Though there are relatively few of these buildings throughout California, most of them are large and crowded; just one collapse could cause hundreds of deaths. Extrication of crushed victims will be difficult, time-consuming, and generally futile. Concrete is brittle and easily cracked during earthquakes, but reinforcing steel can make concrete buildings strong enough to withstand earthquakes. However, concrete columns and beams erected before the mid-1970s often lack enough reinforcing steel to keep them from collapsing or being damaged beyond repair during earthquakes (Figure 53). Seismic retrofits range from as little as $5 per square foot to over $45 per square foot of floor area.

During the Northridge earthquake, several concrete-frame buildings collapsed, and many others came precariously close. At a different time of day, several hundred lives could have been lost at the Bullock's department store building in Northridge (figures 34 and 52) or at the Kaiser Medical Office building nearby (Figure 33). In the 1971 San Fernando earthquake, three such buildings collapsed, killing 52 people. Like Northridge, the San Fernando earthquake occurred in the early hours of the morning, which reduced the number of deaths. The state can't rely on being so lucky in the future.

No single agency is responsible for taking steps to reduce this type of risk in a timely manner. In the private sector, the American Concrete Institute has focused on developing building codes for new concrete construction over the past two decades and only recently has made any significant progress in addressing the problems of seismic evaluation and retrofit. Other volunteer efforts like those of SEAOC have likewise made very little progress.

Three recently funded efforts are encouraging but are proceeding at a slow pace, somewhat like the Caltrans bridge retrofit program before the Loma Prieta earthquake. The National Science Foundation has funded the Repair and Rehabilitation Research Program, a unique collaboration between structural engineers and researchers to develop reliable and practical evaluation and retrofit techniques. FEMA has a project to develop Seismic Rehabilitation Guidelines for all types of buildings throughout the United States. Like the NSF program, it is designed to meet the needs of the entire country and does not focus primarily on needs for information on specific building types commonly found in California. The Commission has a Seismic Retrofit Practices Improvement Program that is focusing on this building type but is only one-tenth the size of the federal effort.


A. Johnson

Figure 53. This office building's exterior cladding affected the way its frame responded to shaking, finally resulting in column failure and demolition. *Inset,* detail.

Recommendation

The Commission recommends that:

- The state continue its support of the Seismic Retrofit Practices Improvement Program but recognize that the pace of this program is slow and is just a small step toward addressing the substantial risk posed by concrete-frame buildings.

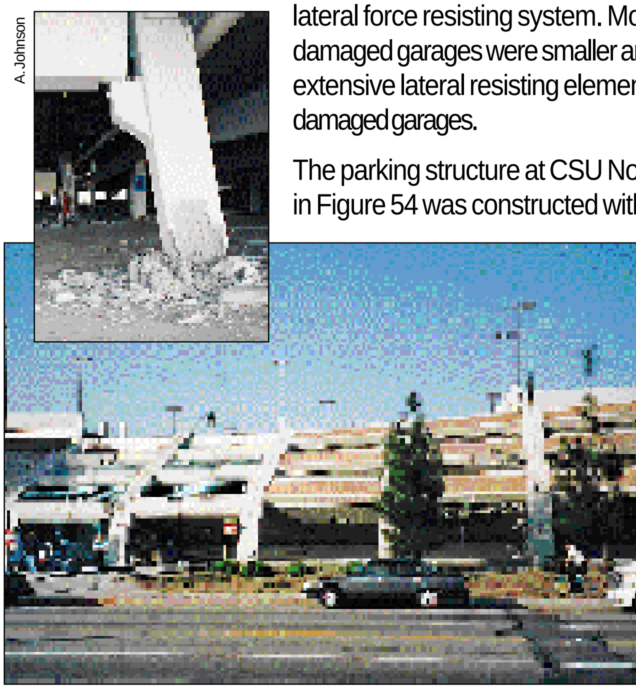
Other recommendations in this report will contribute to addressing this issue, in particular assigning more accountability to the CBSC and establishing a Center for Earthquake Risk Reduction.

Parking Structures

Parking structures sustained far more damage than expected when compared to other types of structures shaken by the Northridge earthquake. At least 34 parking structures out of approximately 100 in the region sustained sufficient damage to require demolition or significant repair. Almost all the parking structures that suffered significant damage were built after 1960. A common characteristic shared by the partially collapsed garages was the presence of at least some precast concrete elements. Several of the partially collapsed garages appeared to have failed due to inadequate ties between both cast-in-place and precast concrete elements and the lateral force resisting system. Most of the undamaged garages were smaller and had more extensive lateral resisting elements than the damaged garages.

The parking structure at CSU Northridge shown in Figure 54 was constructed with precast concrete "tree" columns and girders. The earthquake forces were resisted by exterior moment frames. The structure deflected under the earthquake forces and the combination of large lateral deformations and vertical load caused crushing in poorly confined, critical interior columns, which were not designed to undergo such deformations. It should be noted that not all parking structures at CSU Northridge suffered such extensive damage.

A. Johnson



EERI

Figure 54. This parking structure's exterior frames leaned over when interior columns failed. *Inset,* detail.

A parking structure in Reseda sustained almost total collapse. This structure was constructed with precast concrete beams, planks, and a poured-in-place topping slab. The columns were poured-in-place concrete. The lateral forces were resisted by walls on three sides, but the structure suffered large displacements on the open side that led to both column failure and loss of support for precast units.

In many cases the exterior columns of the parking structures were damaged because their overall height was reduced by walls or spandrels. The Glendale Fashion Center Garage had precast concrete beams and a poured-in-place topping slab. The lateral forces were resisted by concrete walls. Deep spandrel beams linked short, brittle columns that fractured and a portion of the structure collapsed. The Sherman Oaks Galleria South Garage was another structure where concrete columns and beams were subjected to lateral forces for which they were not designed. Figure 55 shows this type of damage.

Poor performance of structural members was also caused in some instances by the incorrect placement of reinforcing steel. A parking structure in the Universal City area provided such an example. The lateral forces were resisted by concrete walls. The reinforcement of one of the concrete walls was not placed as shown on the structural drawings and the wall failed to resist the lateral forces, resulting in damage from large deformations in the structure.

A number of the seriously damaged above-grade parking structures were designed and constructed through the design-build process described earlier, which may have contributed to their difficulties. However, there were several examples of design-build projects that performed similarly to projects where engineers were hired independently from contractors, so this earthquake was not a clear indictment of the design-build process.

Other evidence does more clearly indicate flaws in the design and construction process. For example, since these structures are often built from components designed by many separate engineering firms, no one engineer is typically responsible for the entire structural system. Failures can and did occur because of this division of responsibility.

The damage to parking structures points out flaws in the quality of design, the codes governing their construction, and construction practices. Improvements in the design of parking structures are needed. The Commission believes that the revisions to the UBC that have already been proposed are needed to improve the performance of parking structures. It is reasonable to infer that a significant percentage of existing parking structures throughout California have problems similar to those that collapsed in the Northridge earthquake, since these types of structures are common throughout the state.

Steel-Frame Buildings

The biggest surprise in terms of building performance from the Northridge earthquake, at least to the professionals who deal with seismic design regularly, was the poor performance of steel buildings with moment-resisting frames. Steel buildings have long been viewed as among the most reliable structural systems for resisting earthquakes. They are common for modern highrises, not only in California but throughout the world.

The Northridge earthquake caused unprecedented damage in a significant number of these modern buildings, primarily fractures near the beam-to-column welds and in the columns around the beam-to-column connections (see Figure 56). In most cases these failed connections were not readily apparent, as they are typically hidden by fireproofing, ceilings, and walls, but damaged steel buildings have been located both within and outside the areas of strongest shaking.

The damage generally indicates previously unknown limitations on ductile behavior and raises serious questions about current practice for design and construction of such systems. Fortunately none of the failures resulted in building collapse or loss of life. However, since the earthquake shaking was of short duration, it is an open question as to how the damaged buildings would have performed if the shaking had lasted substantially longer or was of stronger intensity.

Extensive connection failures were found in about two dozen buildings, and moderate and minor connection failures have been uncovered in well over 100 steel-frame buildings in the greater Los Angeles area, both within and outside the near-source region of the Northridge earthquake. Many of these buildings are relatively new, constructed from the 1960s to the 1980s, and a few are more than 20 stories high. Approximately 400 other steel-frame buildings have been targeted for inspection by the City of Los Angeles; as inspections continue, the number of affected buildings continues to grow.

As of December 1994, research had not yet yielded definitive answers as to root cause, appropriate repair methodology, and possible scope of the problem. Some of the contributing causes of failures suggested are:

- Mechanical properties of the thick steel sections currently in wide use.
- Problems with high-deposition welding electrodes and lack of adherence to American Welding Society procedures.
- Improper or missing details.
- Too few members and moment-resisting connections reduced redundancy and provided too few alternative paths for resisting earthquake forces.
- A level of shaking that exceeded the demands considered in the original designs of the structures.
- Design concepts that put the critical sections at the welded joints.

Considerable change has taken place in the design of steel moment-resisting frames over the years. Driven by a desire for long clear spans, designers have specified ever-larger columns and girders. In the 1970s, column flanges were typically 1.0 inch thick and beam flanges might be 0.75 inch thick. Now the flanges of such columns can be over 4 inches thick and those of the beams nearly 1.5 inches. Only a short time ago these sizes would have been considered unprecedented. The effects of these increases in size on metallurgy, residual stresses, and fracture processes have not been researched adequately.

Turner

Figure 55. Short columns in this parking structure failed. Modern building codes now require much more reinforcing steel for such short columns.

EERI

Figure 56. Steel-frame connections were unexpectedly cracked.

Both the state and the City of Los Angeles took actions to deal with the problems of fractured moment-frame welds. On April 6, 1994, the Commission issued an advisory that recommended that the "owners of steel-frame buildings who observed damage . . . are encouraged to contact a civil or structural engineer or architect for an opinion regarding the need to selectively investigate critical areas within their buildings" (SSC, 1994g). On May 11, 1994, Los Angeles issued a memorandum on "The Repair of Cracked Moment Connections in Steel-Frame Structures and Requirements for Connections in New Buildings." In it Richard Holquin, assistant chief of the building bureau, pointed out that these were interim measures only and recommended that the plan check engineer notify the owners that "they may wish to wait on the repair work until results of a test program presently underway for this connection are completed." Because of the economic necessities of repair, many owners of damaged steel-frame buildings proceeded with the city's proposed measures or went substantially beyond them. Some owners decided that the need to reoccupy, or more typically, to maintain occupancy, was so great that it was economically desirable to proceed with interim repairs, even if substantial additional work became necessary at a later date.

MOMENT-RESISTING FRAMES

Moment-resisting frames consist of beams and columns welded together at their connections that bend when the ground moves. These frames do not rely on walls or diagonal braces to resist earthquakes.

Ductile moment-resisting frames will yield in a controlled manner at the beams and joints before the columns yield, thus prolonging the stability of the frame and reducing, if not eliminating, the potential for instability, column failure, and collapse.

In contrast, nonductile frames, most commonly used from the 1950s to the early 1970s, were allowed by building codes prior to 1976. These frames are more flexible but may allow columns to fail and become unstable and collapse in moderate to strong shaking.

In cooperation with SEAOC and other professional organizations, the Commission proposed an emergency code change to the UBC. The change requested deletion of the UBC section that contains a prescriptive connection detail for steel special moment-frame beam-to-column connections. On September 14, 1994, the ICBO board of directors approved the Commission's request and deleted the section. On October 24, 1994, CBSC also adopted an emergency change to construction practice for new steel frames in hospitals, public schools, and state-owned buildings. This change will not apply to other types of buildings until the 1994 UBC is adopted by local governments by mid-1995. To avoid more new steel buildings being built to the inadequate 1991 UBC, the Commission amended its advisory to urge that all local governments also take emergency code adoption measures (SSC, 1994g).

A newly formed joint venture by SEAOC, ATC, and the California Universities for Research in Earthquake Engineering has been formed to address this issue. Known as the SAC Joint Venture, it has been funded by FEMA and OES to undertake comprehensive investigations into the failure of steel-frame connections. The question of the extent of hidden damage to other steel-frame buildings that may have been affected by this or other earthquakes is a significant issue. Inspection of the connections is expensive because finishes and fireproofing must be removed, but damaged connections were found in many buildings examined after the Northridge earthquake that did not show any visible signs of structural damage.

Resolving the reasons for failure and finding solutions also should consider the near-source ground-motion effects associated with active faults in urban areas. Though most of the damaged steel buildings were on the periphery or beyond the near-source area, near-source effects may have contributed to some of the failures and may pose significant risks in future earthquakes (see definitions on page 11).

Areas to be investigated simultaneously should include retrofit techniques for existing undamaged but vulnerable buildings and the design of connections for new buildings. There is a vast inventory of steel-frame buildings throughout the state (and the nation) that use details of construction similar to those that failed. Whether or not these buildings have been damaged in other earthquakes, they are at risk from future earthquakes. Once appropriate retrofit and repair methods are identified, the state should consider providing incentives to encourage owners of buildings to find and repair or retrofit the structures to a condition superior to their original status when leases are renewed or buildings are sold. Without incentive or mandatory inspection and repair/retrofit programs, the expense of dealing with this problem will preclude meaningful progress in reducing earthquake risk.

Unfortunately, very few of the damaged steel buildings were instrumented so that their response to the earthquake could be measured. There were also few free-field instruments in the immediate vicinity of the damaged buildings, so the nature and intensity of the ground shaking to which they were subjected can only be estimated.

Recommendation

The Commission recommends that:

- The state marshal its academic, technological, government, and industry resources to support the SAC Joint Venture to determine how to repair the steel moment-resisting frame connections damaged in the Northridge earthquake.

Seismically Isolated Buildings

There were a few seismically isolated buildings shaken in the Northridge earthquake. They suffered little or no damage, but none was situated close enough to the epicenter to truly test this relatively new approach to earthquake risk reduction. Seismic isolation can be used effectively to reduce the response of buildings to ground motions if isolation systems have suitable force-displacement characteristics that will be maintained over a building's life and if they safely tolerate large displacements while supporting building loads.

However, near-source ground motions, as described in Chapter II, may generate discrete pulses of high ground velocity and displacement to which seismic isolation systems may be particularly vulnerable. If seismic isolation is being considered for future projects, designers should evaluate the effects of near-source motions as well as other unique site effects such as geomorphic and basin-edge effects on seismic isolation systems.

Hospitals

After major urban earthquakes, hospitals can expect to be overwhelmed with the injured. They must be able to withstand the shaking themselves to perform their function of emergency care as well as provide for their existing patients. The 1971 San Fernando earthquake seriously damaged several medical facilities, including the then brand-new Los Angeles County Olive View Hospital. Several of these facilities could not function after the earthquake, and some had to be demolished.

There is a vast inventory of steel-frame buildings throughout the state that use details of construction similar to those that failed.

In response to the recognized need for superior seismic performance by hospitals, and spurred by these spectacular failures, the Legislature enacted the Alfred E. Alquist Hospital Seismic Safety Act (Hospital Act) in 1972. The intent of the act is clear:

> Hospitals, which house patients who have less than the capacity of normally healthy persons to protect themselves, and which must be reasonably capable of providing services to the public after a disaster, shall be designed and constructed to resist forces generated by earthquakes, gravity, and winds.

The Hospital Act proved to be very effective in limiting structural damage in the Northridge earthquake. However, nonstructural damage was extensive. As noted in a draft OSHPD report to its Hospital Building Safety Board:

> Post-1973 hospital buildings and other health care facilities constructed under the requirements of the Seismic Safety Act performed very well with respect to the primary structural systems and with very few problems except for Holy Cross Hospital which has a steel frame and suffered severe structural damage. However, the performance of non-structural parts of the buildings and the equipment and piping systems performed poorly, resulting in extensive damage to the building interiors including flooding, which resulted in the tem-

porary shut down of several post-1973 hospital buildings and the evacuation of patients either fully or partially until extensive repairs and clean up could be effected (OSHPD, 1994a).

The table "Healthcare Buildings Damaged" summarizes the structural and nonstructural performance of hospitals and skilled nursing facilities most heavily impacted by the Northridge earthquake.

Throughout Los Angeles County, 928 patients were relocated because of damage to hospitals (LAFD/EMS, 1994). By comparison, in the 1971 San Fernando earthquake, 17 out of the 23 hospitals in the San Fernando Valley were damaged or destroyed, and 1,327 beds out of 6,751 were lost.

It is not known whether the remaining facilities could have served a larger number of injuries had the earthquake occurred later in the day. The effectiveness and rapidity of emergency measures such as treatment by portable emergency medical centers, use of mutual aid from elsewhere, freeing up capacity by early discharge of patients, cancellation of nonemergency appointments, or transportation of injured patients to more distant undamaged facilities might have been possible, but this has never been tested on a large scale in California.

Only structural damage caused long-term closings. At Holy Cross, for example, nonstructural damage required evacuation on January 17, but the facility was reopened for most services January 24; the trauma and paramedic units reopened February 10. Although nonstructural damage was often very disruptive, repairs and cleanup were typically effected within days. Financial losses to hospitals due to disruption of service are more severe when there is serious structural damage, but the more important loss of ability to serve the community during the hours following the earthquake is more likely to be caused by nonstructural damage (Figure 57).

Performance of Pre-Act Hospitals

Structural damage was greater to pre-act buildings, but many of the two dozen Veterans Administration Sepulveda buildings designed in 1952 experienced only repairable cracking. Good performance in older buildings was associated with reliable types of systems that have not greatly changed over the years (reinforced concrete and reinforced masonry walls) and with regular configurations. Figure 58 illustrates some of the more serious damage in the earthquake to the pre-act St. John's Hospital in Santa Monica.

When the Hospital Act was passed, its authors anticipated that normal replacement of aging facilities would mean that the majority of hospital buildings would be up to the act's standards within a quarter century. However, hospital buildings are not being replaced at the anticipated rate.

Recently enacted SB 1953 (Alquist) requires pre-act hospitals to come into substantial compliance over a 35-year period. Carrying out this new statute will address both structural and nonstructural weaknesses in California acute-care hospitals.

HEALTHCARE BUILDINGS DAMAGED

		NONSTRUCTURAL DAMAGE		STRUCTURAL DAMAGE		
	TOTAL	MAJOR	MINOR	RED-TAGGED (UNSAFE)	YELLOW-TAGGED (RESTRICTED)	GREEN-TAGGED (SAFE)
PRE-ACT BUILDINGS	51	31	20	12	17	22
POST-ACT BUILDINGS	31	7	24	0	1	30

Source: OSHPD, 1994a.

Performance of Post-Act Hospitals

Except for problems with the steel-frame connections at Holy Cross Medical Center and the Henry Mayo Newhall Community Hospital, the structural performance of post-act buildings was excellent. Poor penthouse performance is a concern that can be addressed with minor modifications to OSHPD procedures without major policy changes.

Recent changes to state laws allow OSHPD to post damaged hospitals as safe or unsafe and provide authorization for limited occupancy after disasters, but OSHPD does not have clear authority to prohibit the use of damaged acute-care facilities. Even though the earthquake resistance of these facilities may be severely compromised, OSHPD currently has no clear emergency powers to enforce the directives that are provided on its placards. As a result, hospital owners may keep damaged buildings in operation even if it may be in the best interests of hospital patients, other building occupants, and the general public to redirect acute-care functions to other undamaged facilities nearby. In particular, hospital owners who have previously restored service after a disaster will prefer to avoid adverse public relations that can result when facing a second possible closure if additional damage is discovered.

Nonstructural Damage to Hospitals

When considering the effect of nonstructural damage, it is instructive to look at the three acute-care hospital facilities that had one or more buildings designed and constructed to the Hospital Act, where the disruption was due primarily to nonstructural damage. Holy Cross and Olive View (now named Sylmar) hospitals and six buildings at the Northridge Hospital Medical Center were built to the act. The primary cause of disruption and evacuation at Northridge and Olive View was broken piping and water leakage; at Holy Cross it was damage to mechanical equipment in the heating and air conditioning system. Except as noted, all three suffered (OSHPD, 1994b; McGavin and Patrucco, 1994):

- Sprinkler and other water line breaks and leaks
- HVAC equipment anchorage failures
- Large oxygen tank base failures; leaning tanks
- Toppling of unanchored cabinets and equipment
- Communications failures
- Elevator damage
- Firefighting system failure
- Medical gas failure (except Northridge)
- Backup power outage (except Northridge and Holy Cross)
- Water service outage
- Gas service outage
- Electrical service outage

Though the main hospital buildings at Olive View and Holy Cross were functionally disabled primarily by extensive nonstructural damage, they did suffer some structural damage. OSHPD issued a yellow tag to Holy Cross because it suffered significant structural damage to its steel frame, though the damage was not relevant to the functioning of the hospital in the earthquake's aftermath—it was not discovered until more than a month after the earthquake. Olive View received a yellow tag for structural damage to the penthouse; OSHPD is currently reviewing design procedures for penthouses.

Reitherman

Figure 57. Damage to the heating and ventilation system in this hospital shut it down for a week. Months later, additional structural damage to steel connections was discovered and repaired.

N. Johnson

Figure 58. This older hospital was severely damaged. Lightly reinforced concrete walls lost much of their strength when X cracks formed. *Inset,* detail.

Nonstructural damage in pre-act buildings was significantly greater than in post-act buildings, but it caused widespread, temporary disruptions to essential services in newer hospitals built to Hospital Act requirements.

Water-related components caused the greatest concern. Damage was caused by leakage from sprinkler, domestic water, and chilled water lines; water shortages were caused by the lack of sufficient onsite storage. Twenty-one buildings at healthcare facilities suffered broken nonsprinkler water lines with most of the damage to small lines, less than 2 1/2 inches in diameter, for which bracing is not required by code. Sprinkler line breakage occurred at 35 buildings, all of which was caused by small unbraced branch lines (see Figure 59).

At six facilities (not counting the Veterans Administration's Sepulveda facility), emergency power generator systems failed to operate (Murray, 1994). In some cases, "auxiliary stairwell lighting was not connected to emergency power, necessitating evacuation of patients down totally darkened stairwells" (Snyder, 1994). Emergency power failures also are discussed in Chapter IV.

The fact that two of the largest and newest facilities in the San Fernando Valley—Olive View and Holy Cross—were effectively shut down for the week following the earthquake by nonstructural damage is most troubling and raises issues about whether the Hospital Act's aim to provide functional hospitals is being met. The limited success of the Hospital Act is an example of how simple increases in building code requirements have not necessarily ensured more reliable seismic performance. Many hospital owners have realized this and are departing from conventional code approaches for new hospital designs. OSHPD is now reviewing an ever-growing number and variety of sophisticated designs that attempt to address seismic demands on hospitals that are much more realistic than building code requirements. New and comprehensive design guidelines for achieving seismic performance objectives that are described in earlier sections of this chapter will aid the hospital industry to remain operational after earthquakes.

The Commission believes the performance of nonstructural elements in both pre- and post-act buildings must be improved; otherwise, nonstructural damage will continue to prevent hospitals from functioning at a time when they are most critically needed.

Recommendations

The Commission recommends that:

- Recently enacted legislation requiring the strengthening of nonstructural systems necessary for essential post-earthquake functions be carried out.
- OSHPD, in consultation with the Hospital Building Safety Board, assign the highest priority to quickly retrofitting building components that have proven to be particularly vulnerable and disruptive—sprinkler and other water lines, emergency power, large oxygen tanks, and telephone and radio communications—before requiring retrofits for all the less critical nonstructural items in hospitals.
- OSHPD develop and adopt complete administrative regulations for hospitals, skilled nursing facilities, and intermediate-care facilities and develop and adopt regulations to allow OSHPD to issue minor citations or stop-work orders when violations are observed on construction projects under its jurisdiction.

Elevators

During the 1971 San Fernando earthquake many elevators were severely damaged when their counterweights shook out of their guide rails, endangering the occupants. Consequently, legislation was passed that required that all elevators in California be retrofitted or newly installed to shut down when the elevator is shaken by an earthquake. This shut-down requirement applies to all elevators even though elevators in critical facilities, such as multistory hospitals, are needed for emergency response. Currently, patients must be transported in the stairwells, some of which were dark because of lighting failures immediately following the Northridge earthquake.

Elevators can be designed to withstand earthquake shaking without shutting down unless their counterweights actually do come out of their guide rails. A subcommittee of the California Hospital Building Safety Board is currently examining the feasibility of go-slow elevators. These go-slow elevators would allow hospital staffs to move patients more efficiently after an earthquake without putting the elevator occupants' lives in danger.

Recommendation

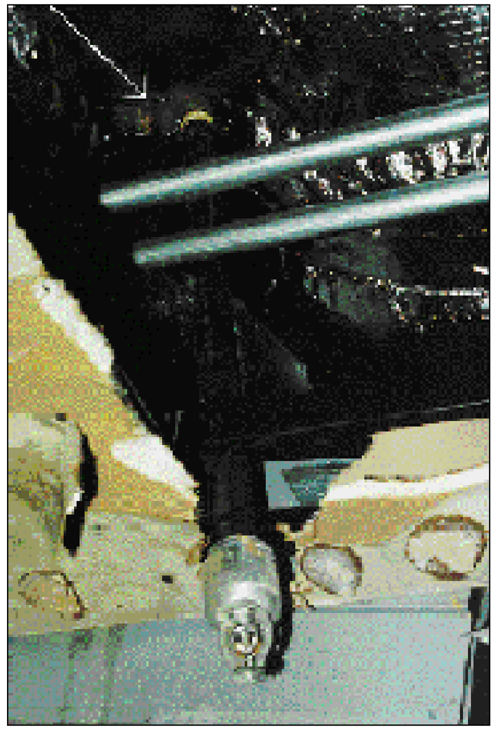
The Commission recommends that:

- Legislation be enacted to require at least one go-slow elevator in each wing of all OSHPD-approved multistory healthcare facilities. This legislation should include the retrofitting of one elevator in all existing multistory healthcare facilities.

Communications

Communications among hospitals and emergency services agencies were seriously disrupted in this earthquake. This disruption extended beyond expectable telephone outages to radio links relied on in earthquakes, as summarized in a report prepared for the Commission:

> During the initial roll call of hospitals on the H.E.A.R. (Hospital Emergency Administrative Radio) system beginning immediately after the quake, there was only a 29 percent response and no response from any hospitals in the most impacted area. . . . H.E.A.R. is dependent on land lines and this could have been a primary cause of the disruption. The Reddi-Net computer system was said to have been 90 percent functional by the Hospital Council but again the hospitals in the impacted area did not receive any messages on the system (Cheu, 1994).



Reitherman

Figure 59. Water from failed sprinkler lines produced costly damage and disruption.

Recommendation

The Commission recommends that:

- Legislation be enacted to require hospitals to install, maintain, and periodically test in realistic exercises redundant emergency communications systems that do not rely on land lines. These systems must connect with emergency responders—police, fire, paramedics, and ambulances—and work within the hospital facility.

Hospital Emergency Plans

Earthquake emergency planning requirements for hospitals are typically guided by the nongovernmental Joint Council on Accreditation of

Healthcare Organizations (JCAHO) through accreditation reviews that a hospital must pass to operate in the United States. JCAHO requires two disaster exercises per year and a written disaster plan that is based on both an internal disaster (typically postulated as a fire) and an external disaster that would generate sudden medical demand (typically a plane crash). Earthquakes do not fit well into the existing JCAHO disaster plans devised for the typical American hospital in that earthquakes are simultaneously an internal and external disaster. For example, Holy Cross or Olive View hospitals experienced water leaks and power and communications problems at the same time that people in the surrounding area were injured and needed treatment. Critiques of hospital earthquake exercises have frequently noted that the exercises are little different from the external disaster (say plane crash) exercises. Elevators are used to transport simulated patients; power is assumed to be normal; no allowance is made for overturned nonstructural elements being nonfunctional; and no provision is made for outside lifelines being unavailable.

A recently passed state law requires hospitals to include all pertinent information regarding the seismic performance of hospital buildings in emergency training, response, and recovery plans (SB 1953, Alquist). However, many hospital disaster training scenarios currently do not address realistic situations where hospitals are damaged by ground shaking and confronted with victims requiring emergency medical aid as well as decisions to evacuate.

Recommendations

The Commission recommends that:

- The Department of Health Services develop regulations in cooperation with JCAHO and OSHPD for recently enacted legislation to mandate that hospitals develop earthquake disaster plans that account for rapid execution of post-earthquake safety evaluations, realistic scenarios of the post-earthquake conditions of their specific buildings, and the availability and reliability of water, power, communication, and other lifeline services.
- OSHPD develop emergency regulations to establish and clarify its authority to post acute-care facilities after disasters and to prohibit the continued use of severely damaged facilities for acute-care purposes.

Essential Services Buildings

California's Essential Services Buildings Seismic Safety Act of 1986 (ESA) regulates the design and construction of new or altered fire stations, police stations, emergency operations centers, California Highway Patrol offices, sheriffs' offices, and emergency communication dispatch centers to increase the likelihood that they will be functional after an earthquake. However, the vast majority of essential services buildings were built prior to the act. It applies only to new buildings and major alterations or additions to existing buildings.

With a few exceptions, essential services buildings functioned effectively after the Northridge earthquake even though some critical components failed to perform at many sites. The state has authorized approximately $45.6 million from a 1990 bond fund for the seismic retrofit of local government essential services buildings.

Fire Stations

Approximately 90 percent of the 105 fire stations were safe for occupancy and were assigned green placards by earthquake damage assessors (Figure 60). Initial assessments of the fire stations indicated several structural and nonstructural problems. Thirty-five stations had door malfunctions; 32 stations had electrical problems; 28 stations had plumbing problems; 19 stations had air conditioning problems; and 18 stations had fallen block walls. Several stations were shut down and later reopened, including one that was shored and then reopened following a one-month closure.

The Los Angeles Fire Department provided a summary of four stations with significant structural damage (LAFD, 1994):

> Fire Station 70 sustained major structural damages to wall and column supports. Estimated preliminary cost of repairs ranges from $650,000 to $750,000.

Fire Station 78 sustained major structural damage to the northwest exterior corner of the building. The Department of General Services and City engineers have structurally supported the integrity of this facility. The exterior hose tower has moved approximately 2-1/2 to 3 inches.

Fire Station 93 sustained major roof support and pilaster damages with an estimated preliminary repair cost of $80,000.

Old Fire Station 27, destined to serve as the Department's museum, suffered major structural damage, and the building has been declared unsafe to enter. A fence has been erected around the southeast corner at the new Fire Station 27 due to potential danger of collapse, and members have been advised not to park in the adjacent parking lot. The first floor north side of the new Fire Station 27 has been boarded up to deflect falling bricks in the event of aftershocks.

The Los Angeles Fire Department's computerized dispatching system completely failed, and dispatching had to be performed with radio communication for the first day after the earthquake. There was a citywide power outage, and emergency generators also failed. Since most of the older fire stations do not have any emergency generators and some of those in the newer stations that did work were too small to power all electrical systems, many stations had blackouts, and many critical systems were inoperable. As an example, the teletype system that provides each station with a detailed printout of specific fire hydrant locations throughout the affected area became inoperable when the power at individual stations was lost. As the event occurred prior to sunrise and many generators failed, station personnel had to contend with the lack of light.

Inoperable doors on fire stations continue to cause serious emergency-response problems. The large openings in the front of typical fire stations tend to create front walls that are inadequately braced and not stiff enough to prevent large amounts of drift, or movement, during earthquakes. Extensive building displacements can jam the doors. If the doors are down when the earthquake occurs, the fire vehicles can't be driven out until the doors are pried up, removed, or knocked out. In the 1971 San Fernando earthquake, it took 20 minutes for a fire engine at the station located on the site of Olive View Hospital to be extricated. In the 1992 Cape Mendocino earthquake, the door of the Petrolia fire station jammed; the time lost while forcing it open contributed to the destruction of the town's general store, post office, and gas station as an earthquake-caused fire burned out of control. Fire station doors jammed in the 1992 Landers-Big Bear earthquake as well.

The Masonry Society

Figure 60. Most fire stations like this one (Northridge Station 107) sustained little or no structural damage, but some had exit and garage doors that were stuck closed.

Although there were no specific instances reported in the Northridge earthquake in which fires were not fought because equipment could not get out due to jammed doors, measures are needed to correct these deficiencies. The Commission believes that either essential services structures should be engineered to reduce drift so the doors are not affected, or the door assemblies should be designed and specified to withstand large amounts of drift. For new structures a design that reduces drift would be preferred, but for older structures a retrofit of the door assemblies would generally be more cost effective.

Recommendations

The Commission recommends that:

- Legislation be enacted to require state and local agencies to review all pre-1986 essential services facilities for their ability to function after earthquakes and that those found deficient be retrofitted.

- Owners and operators of essential services facilities evaluate and make their emergency communication systems, including their power supplies, earthquake-resistant so that they are not lost during periods of most critical need following earthquakes.
- All new and existing multistory buildings with essential services facilities in upper floors be retrofitted or equipped with at least one go-slow elevator.
- A general obligation bond measure be placed on the 1996 ballot to fund a state and local matching grant program or other funding mechanisms to carry out the recommendations in this section.

City Offices and Emergency Shelters

City halls and buildings designated as emergency shelters are not considered essential services buildings under the ESA. However, all are of considerable importance to local communities immediately following a damaging earthquake and during the recovery period. These critical facilities should be subjected to a higher level of design, plan review, and inspection to ensure their continued and timely occupancy following an earthquake.

Recommendation

The Commission recommends that:

- The ESA be amended to require buildings designated as community shelters and those buildings that serve as the place of business for local governments, such as city halls, be placed within the definition of "essential services buildings."

Schools

Schools at every educational level suffered some damage in the Northridge earthquake. Since school was not in session, no injuries occurred to students; however, as this section will show, if the timing had been different, there almost certainly would have been injuries, including some chance of severe or deadly ones. School buildings generally fared well structurally. As with other building types, though, other issues were made clear by this earthquake. Discussed in this section will be the differing jurisdictions, responsible authorities, structural and nonstructural standards, and other issues related to the seismic safety of schools in California.

K-14 Schools

Statewide seismic design and construction requirements for K-14—elementary, secondary, and community college—public schools were mandated following the 1933 Long Beach earthquake. Commonly known as the Field Act, these state requirements were extended to the evaluation and retrofit of existing pre-Field Act buildings with the passage of the Garrison Act (1939) and the Greene Act (1967). The lead agency in the state for carrying out these acts is the Division of the State Architect (DSA). DSA reviews the plans and inspects the construction of public schools. The state's jurisdiction as the building code enforcement agency for schools and the requirements relating to risk reduction of existing pre-act schools does not apply to private schools, the CSU or UC systems.

After earthquakes, DSA acts in an advisory capacity to school districts but does not have authority to post public-school buildings as unsafe or prohibit occupancy. However, after the Northridge earthquake, over 100 public-school campuses were evaluated by structural engineers working under the authority and guidance of DSA, which observed, "No catastrophic collapses were reported of any public-school buildings. Thus, the goals of the regulations and the Field Act were achieved" (DSA, 1994b). Dr. Sid Thompson, Superintendent of Schools for the Los Angeles Unified School District, stated in testimony before the Commission, "I believe in the Field Act. I think that if we hadn't had the Field Act, it would have been a catastrophe."

The Commission believes that public-school buildings, even those built to older codes, performed well in the Northridge earthquake. There was no partial or complete collapse of a public school. No major structural elements such as beams or columns fell; most structural damage could be repaired; and buildings could typically be restored to their previous resisting capacity. This can be attributed to high-quality design, inspection, plan checking, and construction. However, there was enough damage at 127 school campuses in 45 school districts to require damage surveys using the ATC-20 Rapid Evaluation Procedures. As a result of the surveys, 24 buildings were rated unsafe (red tag); 82 were rated limited entry (yellow); all remaining buildings were rated safe to occupy (green). A review of the reports indicates that the engineers had rated the basic structures conservatively. With the exception of some portable buildings and lunch shelters, most structures rated as unsafe were not actually in danger of collapse.

The basic goal of the state's public-school seismic construction regulations is stated in Title 24:

> School buildings constructed pursuant to these regulations are expected to resist earthquake forces generated by major earthquakes of the intensity and severity of the strongest experienced in California without catastrophic collapse, but may experience some repairable architectural or structural damage.

As pointed out in the DSA report (DSA, 1994b) on school performance in the Northridge earthquake and in a private survey (McGavin, 1994), damage can be summarized under a few headings that serve as the basis for risk-reduction measures:

- School buildings constructed before 1976
- Portable or relocatable buildings
- Covered walkways, lunch shelters, and canopies
- Nonstructural falling hazards

Pre-1976 School Buildings

Kennedy High School's administration and gymnasium buildings are unrepairable because of structural damage. The Van Gogh Elementary School is unrepairable because of ground ruptures across the site. Several buildings on the William S. Hart High School campus have been or will be demolished. However, these are extreme cases. Although a vast public-school building inventory was severely shaken by this earthquake, all other buildings suffered much smaller amounts of repairable damage.

It is difficult to summarize the most typical kinds of failures or to make generalizations. There were cracks in walls, spalling of concrete columns at beam-column joints, and cracks in floors, particularly on-grade slabs. This typical structural damage was to be expected from force levels caused by intense shaking. The major portion of the damage was in structures constructed to pre-1976 building regulations, although statistics on performance are not conclusive since the heavily shaken area did not have major school construction in more recent times. An example of typical structural damage is shown in Figure 61.

Community Colleges

The earthquake affected three community colleges (College of the Canyons, Pierce College, and Santa Monica Community College), which experienced damage to light fixtures, suspended ceiling systems, and heavy equipment mounted on roofs. Nonstructural damage at the College of the Canyons totaled over $3.4 million.

The community colleges were administratively part of local school districts until 1968, when legislation created the state community college system and established local community college districts separate from local school districts. However, structures constructed for community colleges are still subject to the design standards and enforcement requirements of the Field Act administered by DSA.

The Legislature recently considered removing community colleges from the Field Act program as a cost-saving measure. The community college chancellor's office argued that community college students are, on average, older than CSU and UC students and thus community colleges should not be held to a higher seismic safety standard. The Commission opposed this legislation largely because neither the community college chancellor's office nor its local districts have properly qualified staffs to take on the responsibilities of building code enforcement. Statewide, 71 community college districts administer a total of 107 campuses, most of which have no building design professionals. The community college chancellor's office in Sacramento also lacks the capability to provide a centralized quality and safety control system for reliable design and construction. The hiring of private contractors to provide plan checking and inspection services was proposed. However, without adequate technical supervision and an independent system of checks and balances as provided by the Field Act, the community college proposal could have resulted in potentially unreliable construction with long-term loss exposure implications for the state.

McGavin

Figure 61. Damage to a concrete column on a two-story elevated walkway at Patrick Henry Junior High School. Note the failure of the guardrail in the background.

This proposed legislation came close to approval by both houses in December of 1993—a two-percent construction cost savings becomes a tempting option when budgets are shrinking. However, the Commission believes that these cost-cutting exercises are shortsighted, particularly since the state has a long-term investment in its school building stock. In any case, the Northridge earthquake reminded community colleges and the Legislature that there is significant value in ensuring consistent and reliable safety and quality in public-school construction through an independent building code enforcement process. The proposed legislation discussed above has been shelved for the time being.

School Construction Procedures

Like K-12 public schools, community colleges administer construction projects even though some districts may lack the knowledge, experienced personnel, or resources to do it properly. Seeking and evaluating bids are also a concern given the state's complex bidding requirements and the districts' lack of construction management resources. For example, public schools must award contracts to the low bidder even when significant concerns exist regarding the bidder's ability to perform. Lacking the funds to hire a project manager to supervise, review, and inspect the low bidders' work, the community colleges and public school districts are not always equipped to ensure quality work.

Dr. Diane Van Hook, superintendent-president of the Santa Clarita Community College District, testified before the Commission:

> I'm also very concerned about the lowest bid concept. For example, I participated in building a college in another community college district. We knew that the lowest bidder was not a good builder, yet there was nothing we could do about it. We could not get the district that had trouble with the bidder to testify because they were in litigation. There was no way we could disqualify that bidder.

Furthermore, though the Field Act allows DSA to submit potential felony violations to district attorneys for prosecution, only major code violations can justify a felony conviction, so there are inadequate methods of citing contractors for minor violations that do not warrant a lengthy felony process. DSA lacks the ability to stop construction work when major violations are discovered, so even if a district attorney is notified of a violation, construction can proceed.

The overall good performance of public schools does not belie the fact that a relatively small number of older Field Act school buildings still pose a life-threatening risk to students. The state's Field Act regulations have evolved somewhat in tandem with the UBC, so public-school buildings constructed before the mid-1970s include a few potentially hazardous systems such as nonductile concrete frames and above-grade concrete parking structures, as well as tilt-ups.

Recommendations

The Commission recommends that:

- Legislation be enacted to amend the Field Act to require DSA to prepare guidelines and procedures for identifying public-school and community college buildings that have potential collapse risks and to require public-school and community college districts to evaluate the seismic vulnerability of buildings and school structures built prior to 1976, correct all defects resulting from design, construction, deferred maintenance, or inflexible utility connections during repairs, alterations or additions and retrofit, replace, or phase out of use structures that pose significant risks to life.

- Legislation be enacted to amend the Field Act to authorize DSA to issue minor citations or stop-work orders when violations are observed on public-school construction projects.
- Legislation be enacted to direct DSA and the California Department of Education to determine whether contract bid evaluations and management of school building construction projects are typically executed by properly trained, licensed (where necessary), and qualified personnel within school districts and determine whether the state needs to establish minimum guidelines and personnel qualifications.
- Legislation be enacted to consider the appropriateness and feasibility of requiring prequalification of potential contractors before the submission of bids.

Portable Classroom Buildings

Several portable or relocatable classroom buildings were seriously damaged in the earthquake. Many units had foundation failures where the cripple walls were racked up to eight inches out of plumb. Some fell to the ground. These failures occurred in structures constructed prior to 1976 with wood foundations. Some were poorly maintained and showed evidence of rotting wood and a subsequent loosening of nails intended to resist seismic forces. See Figure 62.

Relocatable classrooms that are owned by public-school districts that do not comply with the Field Act should already have been removed from campuses. However, the State Allocation Board is still issuing a number of waivers for noncomplying owned and leased buildings.

McGavin

Figure 62. Several portable classrooms were seriously damaged after falling from weak or poorly maintained foundations. *Inset,* detail.

Some districts, under the pressures of increasing enrollments and limited budgets, have resorted to using nonconforming portable buildings. Since these units were classified as temporary, with a life of less than three years, they did not require DSA approval. They were sited without permanent foundations designed to resist lateral seismic forces. In the Northridge earthquake, some of these temporary buildings fell off their supports. These failures point out the need for relatively inexpensive and rapidly obtained factory-built school buildings that are installed on adequate foundations.

DSA policies concerning relocatable buildings on school campuses were under review before the Northridge earthquake. DSA developed a four-part program to address these issues. Three of the four parts went into effect via regulations in December 1994. DSA recently proposed legislation with the sponsorship of the Seismic Safety Commission to deem existing trailer-type leased relocatable classrooms built after 1979 to Housing and Community Development (or Department of Housing) standards compliant with the Field Act and suitable for permanent use as long as deficiencies in light fixture and mechanical grill anchorage and foundation bracing are corrected and positive foundation attachments from the frame to the ground are provided. DSA has proposed a number of other changes to accommodate the fact that school districts need to obtain inexpensive units rapidly, while also correcting the present problem of units avoiding Field

Act requirements. They have suggested that the state allow public schools to use federally approved portable classrooms as long as they are adequately attached to their foundations and as long as light fixtures and other nonstructural elements are braced.

Recommendations

The Commission recommends that:

- Legislation be enacted to require public school districts and community colleges to attach portable classrooms to foundations and abate life-threatening nonstructural hazards as proposed by DSA.
- The DSA Field Act Advisory Board work with DSA to develop appropriate legislative language and implementing regulations.

Covered Walkways, Lunch Shelters, and Canopies

These structures normally consist of flat wood-frame roofs supported on steel or concrete vertical cantilever columns embedded in concrete foundations. Some cover large areas or extend for several hundred feet, and all usually connect or abut one or more buildings. The concrete columns are often subject to larger distortions than the adjacent classroom buildings. See figures 61 and 63.

Many of these structures suffered damage at their intersection with other covered walkways or with buildings. The main types of damage were:

- Connection failures caused by wood beams slipping off beam seats
- Connection damage caused by pounding between structures
- Spalling of concrete at the top of columns
- Racking of excessively flexible structures

Figure 63. The lunch shelter at Danube Elementary School leaned over about one foot.

McGavin

Poor maintenance in some instances and less-than-adequate separation joints contributed to the extensive earthquake damage. The lack of maintenance funds from the state and the widespread practice among school districts of deferring the painting, replacement, or repair of leaky roofs or dryrotted or otherwise damaged building elements is a growing contribution to life-threatening situations in public schools.

Recommendations

The Commission recommends that:

- The Legislature develop an adequate funding source for addressing deferred maintenance in public schools.
- Legislation be enacted to direct public schools to review walkways, shelters, and canopies to identify and retrofit those that might endanger students during earthquakes.

Nonstructural and Building Contents Hazards

Nonstructural damage in schools was common. Children certainly would have been hurt or killed by falling elements if the earthquake had happened during school hours.

Nonstructural components were not addressed in the state's regulations for new construction until the mid-1970s, and the San Fernando Valley contained relatively few newer school buildings, so this earthquake did not test the adequacy of current procedures.

According to DSA, light fixtures fell onto desks or to the floor in approximately 100 classrooms. See Figure 64. Cracked partition walls, fallen ceiling tiles, overturned file cabinets, broken window panes, failed light fixture supports, and broken sprinkler water lines were evident in many school buildings located in the strongly shaken area. DSA found many methods for reducing nonstructural damage were quite effective in this earthquake. The older buildings had proportionally more damage, which suggests that many of these hazards can be reduced by retrofitting existing schools with current methods (see Figure 65).

Had the students been at their desks during the earthquake, injuries could have been minimized if the required "duck, cover, and hold" training worked as intended. However, even these measures would not have prevented all serious injuries. Avoidance of injuries requires dealing with the hazards:

- Light fixtures and other heavy overhead items need backup support or safety wires to attach them to the structure and reduce falling threats.
- Tall file cabinets, bookshelves, library shelving, televisions, and other heavy objects overhead must be anchored to floors or walls.

The voluntary abatement of nonstructural hazards has not proceeded in the face of numerous competing issues and a shortage of funds. DSA and OES, through the Bay Area Regional Earthquake Preparedness Project, published voluntary guidelines in 1990 titled *Identification and Reduction of Nonstructural Earthquake Hazards in California Schools*.

Recommendations

The Commission recommends that:

- All public-school and community college districts evaluate nonstructural elements and abate unacceptable hazards. The Field Act should be amended to require DSA to adopt retroactive, mandatory retrofit standards regarding nonstructural hazards. Public-school and community college districts should be required to abate nonstructural and building contents hazards when undertaking major alterations, additions, renovations, or repairs. In any event, retrofits should be completed no later than 2010.
- A percentage of future school bond proceeds be used to abate life-threatening nonstructural and building contents deficiencies in public schools by 2010.
- Legislation be enacted to require personnel at every school district facilities office to be trained to recognize nonstructural hazards and the effective installation of restraints and anchorages and to require an annual refresher briefing on emergency plans for every administrator and teacher.

McGavin

Figure 64. Falling light fixtures in over 100 classrooms would have posed significant threats to students and teachers had the earthquake occurred during school hours.

Private Schools

The design and construction of privately owned schools is governed by the Private School Building Safety Act of 1986. It requires either an architect or civil or structural engineer to be used for the design of new or altered private schools. The local code enforcement agency must use a structural engineer for design review. The owner must provide for special inspection, and the designer must observe construction.

OES

Figure 65. Though less life-threatening than light fixtures, ceiling tiles were a major property loss that could have been reduced with modern bracing techniques.

State law allows existing collapse-risk private-school buildings to continue to be used for education. Very little is known about the seismic resistance of private schools. They are not subject to the Garrison and Greene acts that required seismic upgrades in the 1960s and 1970s for public schools. In 1983 the Commission mailed a questionnaire to private-school administrators asking for data on buildings containing more than 100 occupants. Though the results were incomplete, they did show that at that time over 21,000 private-school students and staff were housed in buildings built before 1950 (Figure 66).

Private-school trustees and administrators who are responsible for the safety of their students may not be aware of the potential seismic risk

Youssef

Figure 66. Life-threatening structural hazards such as this are still allowed in older private schools throughout California. Most of them have been eliminated in our public schools.

to students in some of their buildings. Nevertheless, because of the consequences of a failure of one of these school buildings, the state should assign a high priority to identifying and abating collapse-risk buildings and life-threatening nonstructural hazards.

Preschools are not covered by either the Field Act or the Private School Building Act. New and altered buildings follow the same building standards and enforcement procedures applicable to nonschool uses. Moreover, there are no requirements to address the risk of collapse-hazard buildings housing preschools or nonstructural hazards. A number of preschools are housed in older buildings that were previously condemned for use as public schools because of seismic risk.

Recommendations

The Commission recommends that:

- Legislation be enacted requiring that at the time of sale or renewal of leases, private-school and preschool buildings housing 25 or more students and constructed before 1986 be evaluated by a structural engineer and that life-threatening earthquake risks, both structural and non-structural, be mitigated.
- Legislation be enacted to require private schools to identify and abate nonstructural and building contents hazards in buildings housing students and in classrooms.

School Emergency Plans

State laws require all public and private schools with more than 50 students to prepare earthquake response plans and to exercise the plans with duck and cover drills each school quarter. Although the laws require each school to designate a person to be responsible, there is no other reporting or performance requirement.

Fortunately, the Northridge earthquake did not test these plans since it occurred outside school hours. However, according to testimony given to the Commission, many of these plans are out of date, and communications equipment, tools, and supplies are not readily available. Not having up-to-date plans or the supplies and equipment they are based on renders this state requirement ineffective. Given the level of life-threatening nonstructural risks and the potential for communitywide disruption after a damaging earthquake, these plans and exercises are essential to the safety of school children.

Recommendations

The Commission recommends that:

- Legislation be enacted to clarify that laws requiring school emergency plans are mandatory and that public-school administrators, boards, and private schools are accountable for compliance.
- Legislation be enacted to direct the California Department of Education to provide up-to-date guidelines specifying the minimal requirements for these plans, including equipment, tools, supplies, and frequency of exercises.

Higher Education Facilities

The performance of state government buildings in the Northridge earthquake can perhaps be best summarized through the experience of its two university systems, the CSU system with 20 campuses and the UC system with nine campuses. The Northridge earthquake affected the CSU campuses at Los Angeles (CSU Los Angeles)—which experienced light damage, mostly nonstructural—and at Northridge (CSU Northridge)—which sustained substantial damage. The earthquake also affected the UC campus at Los Angeles (UCLA).

The two university systems share many statutory similarities with respect to earthquake design provisions. CSU is “exempt from local enforcement of earthquake design requirements but [is] subject to the provisions of the Riley Act seismic design standards set forth in Title 24 California Administrative Code or in the local building codes, whichever is more restrictive.” UC is not required “by statute to obtain a local building permit for its buildings or to have seismic design reviewed by local building departments, any State agency, or independent third-party” (McClure, 1984). Both UC and CSU have building code enforcement responsibilities assigned to facilities managers, which means that there is often a potential for conflicts of interest between internal advocates for safety and internal advocates for low budget and quick construction. Unlike public K-14 schools, UC and CSU periodically suffer from the lack of a strong, independent building code enforcement authority. In 1990, the Commission assessed the adequacy and status of seismic safety programs within the UC and CSU systems in *Report to the Governor on Executive Order D-86-90.*

California State University, Northridge

CSU Northridge suffered substantial damage, both structural and nonstructural. The campus is very near the epicenter of the earthquake and was subjected to intense shaking. The damaged structures were both new and old (up to 30 years), and each had somewhat different problems.

- *Parking Structure C* at CSU Northridge was one of the most spectacular failures in the Northridge earthquake. The lateral force resisting system for this structure, completed two years ago, relied on moment-resisting concrete exterior frames to resist earthquake forces in the central eight bays of the exterior perimeter frame in both the north-south and east-west directions. The remaining portions of these perimeter frames were not part of the lateral force resisting system. The columns and beams were precast, and the slabs were poured-in-place, post-tensioned concrete. This structure collapsed on the east side and partially collapsed on the west side; it is a total loss. “The slumping concrete and steel ghost . . . has become the photographic icon for destruction wrought by the temblor,” according to a February 11, 1994, report in the *Los Angeles Times.*
- *Science Buildings 1, 2, 3* and *4* are three-story concrete-wall structures. Science 1 and 2 are older structures that were designed by the, then, Office of the State Architect. Each contains a significant number of interior walls. Some of the walls were damaged, but the most significant damage was to the contents, both from the earthquake and the fires that followed. Science 3 and 4 were built in the last four years and though earthquake-resistant walls were used extensively, they were damaged and will have to be repaired.
- *Oviatt Library* was built in 1971; two wings were added in 1990. The original structure is a four-story concrete-wall building with concrete floors and two basement levels below grade. The wings, also four stories with a single basement level below grade, use steel-braced frames to resist lateral forces. The library sustained substantial architectural damage—notably ceiling collapse. Most books fell from their shelves, although many of the bookshelves remained standing, undoubtedly because the shelving had been seismically braced as part of a systemwide program for library shelving. An exterior canopy was damaged at the connections between the older central structure and the additions. The original portion of the structure suffered minor wall cracking but no serious structural damage and was placed back into operation for the fall 1994 semester. However, the newer wings suffered substantial structural damage. Thick steel plates supporting columns at diagonally braced frames cracked. The precast panels were damaged in some locations and one diagonal brace buckled in the east wing. Based on the damage, the building was red-tagged. The retrofit of the

steel-braced frames in the wings will take many months.

- The *Business Administration and Economics*, the *Education,* and *Engineering Addition buildings* were near completion at the time of the earthquake. In each structure, welded-steel moment-frames are used as the lateral force resisting system. These structures sustained damage to moment-frame connections, although nonstructural damage was not severe. Repair of the buildings was completed by the beginning of the fall 1994 semester.

Damage from future major earthquakes could close university campuses for entire terms, or permanently.

CSU made major changes to its procedures for new construction and retrofit of existing buildings after the Loma Prieta earthquake and is not considering significant policy changes as a result of damage from the Northridge earthquake. Administrators and CSU trustees believe the CSU Seismic Review Board, which was formed in 1991, its Seismic Retrofit Program, and the policy described below have been an effective force in helping to prioritize resources. The essence of the CSU trustees' seismic safety policy is as follows:

> It is the policy of the Trustees of the California State University that to the maximum extent feasible by present earthquake engineering practice to acquire, build, maintain, and rehabilitate buildings and other facilities that provide an acceptable level of earthquake safety for students, employees, and the public who occupy these buildings and other facilities at all locations where University operations and activities occur. The standard for new construction is that it meets the life safety and damageability objectives of Title 24 (CBC) provisions; the standard for existing construction is that it provides reasonable life safety protection, consistent with that for typical new buildings. The California State University shall cause to be performed independent technical peer reviews of the seismic aspects of all construction projects from their design initiation, including both new construction and remodeling, for conformance to good seismic resistant practices consistent with this policy. The feasibility of all construction projects shall include seismic safety review and shall be determined by weighing the practical implications and cost of protective measures against the severity and probability of injury resulting from seismic occurrences (CSUCCP, 1993).

CSU, even in the absence of new bond funds, is doing what it can to apply this policy, according to testimony presented to the Commission. The CSU Seismic Review Board is the responsible agent for implementation and conduct of independent peer reviews.

The UCLA Campus

Of the approximately 130 structures on the UCLA campus, 18 were significantly damaged in the Northridge earthquake (Bocchicchio, 1994). Of the 18, seven had been rated as "very poor" and two "poor" in 1993 seismic evaluations; the other nine were rated as less vulnerable. Most of the damage was to nonstructural elements, although there was noteworthy structural damage:

- *Royce Hall*, built in the 1920s, sustained structural damage. It is a popular symbol of the University and houses the main campus auditorium (see Figure 67) and classrooms for a diverse group of academic programs offered by the College of Letters, Arts, and Sciences. This structure had been identified as one of the seven "very poor," or most vulnerable, structures on campus. The structural damage was primarily in the two towers at the entrance. Because these towers stand over the main entrance, it was necessary to close the building. The seismic deficiency of these towers had been noted in a UCLA seismic committee review and a design team was in the process of designing seismic retrofit measures at the time of the earthquake.
- *Dicksen Art Building,* a concrete-wall building, sustained damage to its walls and exterior damage to stucco, concrete, and brick fascia. This building has been identified as requiring additional lateral force resisting elements to prevent future damage or failure.

- The *UCLA Medical Center* suffered minor structural damage including cracked walls and cracked beam column joints, particularly at the second floor of the Neuropsychiatric Institute and Hospital. There was also pounding damage between many of the older structures.

Many of the older buildings sustained damage to URM and hollow clay tile partitions. These partitions are seldom part of the formal lateral force resisting system, but they do resist some of the force and provide much of the damping for the building.

UC administrators are not contemplating significant changes in campus policies as a result of the Northridge earthquake. An informal effort is being made by the office of the president to review recent designs to determine whether they include details and concepts similar to those that were the source of damage in the earthquake. If they do, the engineer is asked to explain how the proposed design will provide the desired performance. UC believes its first priority for retrofitting must be to address the buildings known to pose significant life-threatening risks.

UC and CSU Seismic Safety Programs

The UC and CSU building code enforcement systems lack the independence and consistency provided by the DSA for other public schools. The Commission periodically learns of compromises and priority adjustments affecting seismic safety on UC and CSU campuses that indicate that lower levels of seismic safety are still tolerated by the state in its higher education facilities.

However, with the exception of the inherent lack of independence in the UC and CSU building code enforcement process, the gap in seismic safety between the Field Act and the UC and CSU systems has narrowed in recent years because of substantial and very encouraging improvements within the systems.

Survival of Academic Programs

The extensive damage to the CSU Northridge campus illustrated how buildings can protect life safety and yet still be hard-pressed to restore academic and research programs. Though CSU Northridge demonstrated how to improvise and reopen quickly, it wasn't easy; damage from future major earthquakes could close university campuses for entire terms, or permanently. The experience of the near closure of Stanford University after the 1989 Loma Prieta earthquake reinforces this clear threat to academic programs. Given the location of many of our campuses near major faults, additional attention is needed to deal with this threat.

Sabol

Figure 67. Large sections of a heavy plaster ceiling came down in Royce Hall. At another time of day, injuries and possibly deaths would have resulted.

Recommendations

The Commission recommends that:

- The Governor direct UC and CSU to require each campus facilities manager to determine key buildings and academic functions needed to restore key educational and research programs after earthquakes in addition to life safety concerns that must continue to be the first priority of campus retrofit programs. Earthquake response plans should be established to redirect or restore such critical academic and research functions in a timely manner for realistic earthquake scenarios. The UC and the CSU systems must review the pacing and priorities of their seismic retrofit programs, including nonstructural risk-reduction efforts, to ensure that they will be capable of resuming critical educational and research programs after major earthquakes in a timely manner.
- The Governor direct UC and CSU to establish the goal that all life-threatening structural

and nonstructural seismic hazards in UC and CSU buildings be retrofitted by the year 2005.

- UC and CSU prepare a capital budget plan that would allow completion of seismic retrofitting of all university buildings that pose unacceptably high seismic life safety risks by the year 2005.
- Legislation be enacted to require UC and CSU to adopt guidelines that trigger the seismic retrofit of all hazardous, life-threatening university buildings upon major alterations, reoccupancies, additions, renovations, or repairs.
- DSA complete its effort to develop building seismic retrofit guidelines in cooperation and concurrence with UC, CSU, and other interested organizations by May 1995.
- The Governor direct to the UC Board of Regents and the Legislature to enact new laws to ensure that UC and CSU abide by the minimum seismic design standards and enforcement practices of Title 24, including independent peer review, thorough plan checking, field inspection, and the monitoring of construction by designers for all new, remodel, and retrofit projects.
- The university systems adopt stop-work and citation authority for their code enforcement personnel to reduce minor violations of and enhance compliance with Title 24.
- The Legislature provide sufficient funds for the seismic retrofit of UC and CSU buildings by the year 2005.
- Legislation be enacted to approve the use of program-based budgeting for state seismic retrofit programs as opposed to the current project-phased budgeting that requires delays and added costs due to multiple legislative approvals of each project.